ATOMS AND ELECTRONS

J. W. N. Sullivan

DORAN'S
MODERN
READERS'
BOOKSHELF

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BY

J. W. N. SULLIVAN

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GENERAL INTRODUCTION

Of all human ambitions an open mind eagerly expectant of new discoveries and ready to remold convictions in the light of added knowledge and dispelled ignorances and misapprehensions, is the noblest, the rarest and the most difficult to achieve.

JAMES HARVEY ROBINSON, in *"The Humanizing of Knowledge."*

It is the purpose of DORAN'S MODERN READERS' BOOKSHELF to bring together in brief, stimulating form a group of books that will be fresh appraisals of many things that interest modern men and women. Much of History, Literature, Biography and Science is of intense fascination for readers to-day and is lost to them by reason of being surrounded by a forbidding and meticulous scholarship.

These books are designed to be simple, short, authoritative, and such as would arouse the interest of intelligent readers. As nearly as possible they will be intended, in Professor Robin-

son's words quoted above, "to remold convictions in the light of added knowledge."

This "adding of knowledge" and a widespread eagerness for it are two of the chief characteristics of our time. Never before, probably, has there been so great a desire to know, or so many exciting discoveries of truth of one sort or another. Knowledge and the quest for it has now about it the glamour of an adventure. To the quickening of this spirit in our day DORAN'S MODERN READERS' BOOKSHELF hopes to contribute.

In addition to the volumes announced here others are in preparation for early publication. The Editors will welcome suggestions for the BOOKSHELF and will be glad to consider any manuscripts suitable for inclusion.

THE EDITORS.

CONTENTS

CHAPTER I: *Units and Notation*

ATOMS AND ELECTRONS

Chapter I

Units and Notation

DIMENSIONS.—All physical magnitudes are measured in terms of the three fundamental quantities, Length, Mass, Time. When we wish to particularise, we denote these fundamental magnitudes by the letters L, M, and T respectively. Any magnitude which is not simply a length or a mass or a time is derived from them. Thus an *area* is a length multiplied by a length. If we wish to express this fact we say that the Dimensions of an Area $= L \times L = L^2$. Similarly, a velocity is a length divided by a time. Its dimensions are L/T. An acceleration is the rate of increase of a velocity. A stone falling to the earth has an acceleration, since it is moving faster and faster. An acceleration is a velocity divided

by a time, and therefore its dimensions are L/T^2. A momentum is a mass multiplied by a velocity. Its dimensions are therefore ML/T. These examples suffice to illustrate the general idea.

Metric System.—Throughout all civilised countries scientific men use the metric system of units. The fundamental units are: for length, 1 centimetre; for mass, 1 gramme; for time, 1 second. This is called the centimetre-gramme-second system or, as it is usually written, the C.G.S. system. For those not used to measuring quantities in centimetres and grammes, it may be useful to see how they compare with English units. A centimetre is about 0·39 of an inch; a gramme is about 0·035 of an ounce. The unit of velocity, on this system, is one centimetre per second. The unit of momentum would be one gramme moving with a velocity of one centimetre per second. A very useful notion in science is the notion of *force.* This term has a perfectly precise meaning. The force acting on a mass is measured by the velocity imparted to that mass in the unit of time. On the C.G.S. system, unit force is that force

which gives to a mass of 1 gramme a velocity of 1 centimetre per second in a second. This unit of force is called a *dyne.*

In the metric system, a very convenient system of prefixes is used which play the part of multipliers or dividers. Thus the prefix "mega" in front of some unit, such as a dyne or a gramme, means a million dynes or grammes. The prefix "milli," on the other hand, divides the unit by a thousand. Thus a milligramme is a thousandth of a gramme. We append a table of these prefixes.

mega	is equivalent	to	multiplying	the	unit	by	1,000,000
myria	"	"	"	"	"	"	10,000
kilo	"	"	"	"	"	"	1,000
hecto	"	"	"	"	"	"	100
deka	"	"	"	"	"	"	10
deci	"	"	dividing	"	"	"	10
centi	"	"	"	"	"	"	100
milli	"	"	"	"	"	"	1,000
micro	"	"	"	"	"	"	1,000,000

A centimetre, therefore, as its name denotes, is the hundredth part of a metre. A kilogramme is a thousand grammes. And so on.

Electrostatic and Electromagnetic Units.—The reader of this book will notice that quantities of electricity are sometimes expressed in

what are called electrostatic units and sometimes in electromagnetic units. Both systems of units are constantly employed in physics, and they exist because there are two radically different ways of measuring electric magnitudes. The reader probably knows that there are two kinds of electricity, positive and negative. Two electric charges of the same kind repel one another; if of unlike minds, they attract one another. It is on this property of attraction or repulsion that the electrostatic system is based. The electrostatic definition of a unit quantity of electricity is as follows: The unit quantity of electricity is that which, when concentrated at a point at unit distance in air from an equal and similar quantity, is repelled with unit force. On the C.G.S. system the unit distance is one centimetre and the unit force one dyne. The unit magnetic charge, or magnetic pole, as it is called, is defined in a similar way.

The electromagnetic system, on the other hand, starts with the dynamic, not the static, properties of electricity. A wire conveying an

electric current produces a magnetic field. The lines of magnetic force exist as circles round the wire. If we imagine the wire itself to form a circle, we see that there will be a certain magnetic force at the centre of this circle. This leads us to the electromagnetic definition of the unit quantity of electricity. We proceed in two steps. We first define the unit current as such that, if it is flowing in a circular arc 1 centimetre in length where the circular arc forms part of a circle having a radius of 1 centimetre, then it will exert a force of 1 dyne on a unit magnet pole placed at the centre of the circle. This defines the unit current. We get to the unit quantity of electricity by saying that it is the quantity conveyed by the unit current in 1 second. The electromagnetic unit of quantity is enormously greater than the electrostatic unit. It is thirty thousand million times bigger. The ratio of the electromagnetic to the electrostatic unit is, in fact, equal to the velocity of light. This is no mere meaningless coincidence. Maxwell showed that this ratio gave the velocity of propagation of elec-

tromagnetic waves, and this velocity is precisely the velocity of light. This was one of the chief points confirming the theory that light itself is an electromagnetic phenomenon.

Large and Small Numbers.—Physicists often have to express very large and very small quantities, and to that end they have adopted a useful and simple convention. A large number like ten million is not written 10,000,000 but as 10^7. The figure 7 shows how many 0's are to be written after the 1. If the number had been thirty million it would have been written 3×10^7. Thus $100 = 10^2$; $1,000 = 10^3$; $10,000 = 10^4$; and so on. Such numbers as 10^{24} or $3{\cdot}5 \times 10^{24}$ would be tedious to write out, and they are of frequent occurrence.

Similarly, very small numbers are expressed much more conveniently in this way. But the minus sign is prefixed to the figure above the 10. Thus one millionth is 10^{-6}. One million millionth is 10^{-12}. Seven one hundred-thousandths is 7×10^{-5}. Thus $1/10 = 10^{-1}$; $1/100 = 10^{-2}$; $1/1000 = 10^{-3}$; $1/10000 = 10^{-4}$; and so on. So that when we say that the weight of a

hydrogen atom is $1{\cdot}65 \times 10^{-24}$ gramme, the quantity we express in this way is

$$\frac{1{\cdot}65}{1{,}000{,}000{,}000{,}000{,}000{,}000{,}000{,}000}$$

of a gramme. Similarly, when we say that the velocity of light is 3×10^{10} centimetres per second, the number we are expressing is 30,000,000,000 centimetres per second.

Chapter II: *Atoms and Molecules*

Chapter II

Atoms and Molecules

§ 1. *The Atom*

THE theory that any piece of matter may be divided up into small particles which are themselves indivisible was a speculation familiar to the ancient Greeks. It is a theory which, unless it be enunciated with some care, has been found by some people to be ambiguous. For the indivisibility attributed to the ultimate particle or *atom* may have reference either to practical or to mental operations. There are philosophers who have worried themselves as to how it is possible to conceive any particle of matter, however small, as ultimately indivisible. For, they argue, if the small particle exists at all it must occupy space and have a shape. Something still smaller, therefore, something occupying only half the space, could be imagined: the atom could be pictured as divided into halves or quarters and

so on. And yet, although it seems impossible for thought to stop at any point in the process of dividing up a piece of matter, it is also very difficult, as can be shown by ingenious arguments, for thought to go on with the process indefinitely. And so an interesting *impasse* is arrived at.

Now it must be clearly understood from the beginning that this is not the sort of indivisibility with which science is concerned. The scientific use of the term has reference purely to practical scientific methods. The indivisibility ascribed to the atom was merely an enunciation of the fact that smaller particles than atoms were not found to occur in any of the processes known to science. Nothing whatever was asserted about any supposed "inherent indivisibility" of the atom. An atom of a substance was merely the smallest part of that substance which took part in any known chemical processes. The whole conception of the atom was first made really definite and fruitful by John Dalton in 1803. He asserted that every irreducible substance, or "element," was composed of atoms indivisible in the sense de-

scribed above. All the atoms of every given element were precisely similar, and, in particular, had the same weight. The atoms of different elements were different and, in particular, had different weights. But besides the chemical elements, that is, substances which cannot be dissociated into other substances, there are chemical compounds. The atoms of the elements constituting a compound unite with one another in a perfectly definite way, and Dalton gave the laws according to which these combinations are effected.

The Atomic Theory of Dalton was a tremendous success. The whole of chemistry since his time has been based on it. To describe even a small part of the consequences of the atomic theory would be beyond our scope, but we must here call attention to one very important classification to which the atomic theory led. By very careful measurements, undertaken by many men and extending over many years, the weights of the atoms of all the different primary substances, or elements, known to science have been determined. The weights, as usually given, are, of course,

relative weights. If we denote the weight of an atom of oxygen by 16, then helium, for example, will have the atomic weight 4, copper will be 63·57, and hydrogen will be a little greater than unity, viz., 1·008. The heaviest element known, uranium, has an atomic weight of 238·2.

Now when all the elements known are arranged in order of increasing atomic weight the highly interesting fact emerges that their properties are not just chaotically independent of one another. They fall into similar groups, recurring at definite intervals. These relations, although they are not of mathematical definition, are quite unmistakable, and show that there is a connection between chemical properties and atomic weights. Such a connection is quite inexplicable if each atom is regarded as a perfectly simple and irreducible structure having no essential relations to the atoms of any other elements. If the atom be regarded as something possessing a structure, then the similarities between different elements may be attributed to similarities in their atomic structures, the heavier atoms being, as it were, more

complicated versions of the same ground plan. We shall see that there is much truth in this view.

Even as early as 1815 the idea had been put forward by Prout that all the chemical elements were really combinations of one primordial substance. Prout supposed this primordial substance to be hydrogen. On comparing different atomic weights he was led to the conclusion that they were all whole multiples of the atomic weight of hydrogen, so that if the weight of hydrogen be represented by 1, then all the other atomic weights would be whole numbers. Every atom, in this case, could be considered as built up from a definite number of hydrogen atoms. The determinations of atomic weights in Prout's day were not sufficiently accurate to warrant this conclusion, and when more accurate measurements showed that a large number of atomic weights are not whole multiples of hydrogen, Prout's hypothesis was abandoned. But recent work, as we shall see, has shown that Prout's hypothesis is much closer to reality than had been supposed.

§ 2. *Elements and Compounds*

The theory that all matter is built up out of atoms was invented, as a scientific theory, to explain certain phenomena which belong to the science of Chemistry. The universe of the chemist is, at first sight, a very bewildering universe. He is concerned to find out what he can about the properties of all the substances that exist. Now there are hundreds of thousands of such substances. Gold, lead, iron, table salt, air, water, gum, leather, etc., etc., is the mere beginning of a list that it would take months simply to write down. The chemist is concerned with every one of these substances. And if he found that all these substances were quite independent of one another, that there were no relations between them, then he would probably give up his task in disgust. For, in that case, he could do nothing but draw up a gigantic catalogue which would, at most, be of some practical use, but which would possess no scientific interest. But even before the rise of a true science of chemistry, men had become aware that all the different substances on earth

are not wholly unrelated to one another. The old alchemists, chiefly by mixing different substances together and then heating them, found that they could change some substances into others. Some of their results were perfectly genuine; they did effect some of the transformations they claimed to have effected. In other cases, they were either mistaken or else imposing on the credulity of their disciples. Many of them claimed, for instance, that certain "base" metals, on being mixed with other substances and then heated, could be turned into gold. We know that this is impossible. But one main idea emerged from their work. They learned to distinguish between the simple substance and the compound substance. It is true that this idea emerged in a very curious form; they did not think so much of simple substances as of primary principles, such as maleness and femaleness, which were somehow incorporated in different substances in different degrees. But the idea of the simple and compound substance, although in a vastly different form, is the basis of the science of chemistry.

Out of all the substances known to exist,

the chemist distinguishes a certain number as being "elements." An element is a substance which cannot be decomposed into anything else. It happens that there are remarkably few of them. Nearly every one of the hundreds of thousands of substances known can be decomposed into other substances. When this decomposition is carried as far as it will go, we find that the substance in question is really built up out of a certain number of the substances called elements. There are about ninety of these elementary substances. In the little list of substances we have just given, for instance, gold, lead, and iron are elements. Table salt is a compound of two elements called sodium and chlorine. Air is a mixture of various elements of which nitrogen and oxygen are the chief. Water is a compound of two elements, hydrogen and oxygen. Gum and leather are more complicated compounds.

Now it is interesting enough to know that all substances are either elements or can be decomposed into two or more elements. But the most interesting aspect of this fact, and what makes it of great scientific importance, is that

when elements combine to form a substance they always do so in exactly the same proportions. When hydrogen combines with oxygen to form water, for instance, exactly the same proportions of hydrogen and oxygen are concerned. We will illustrate this very important law by considering the decomposition of that well-known substance sal ammoniac. It is a pure solid substance. If it be heated it turns into a mixture of two gases. These two gases can be separated from one another and are found to be ammonia gas and hydrochloric acid gas. Now the ammonia gas can in its turn be decomposed into a mixture of the two gases, nitrogen and hydrogen, and these two gases can be separated from one another. The hydrochloric acid gas can also be decomposed. It can be decomposed into chlorine and hydrogen. We have now decomposed our sal ammoniac into three substances, nitrogen, hydrogen and chlorine. Each of these three substances is an element; no one of them can be decomposed into anything else. And we can find in what proportions they combine to make sal ammoniac. If we began our experiment

with 100 grammes of sal ammoniac we should have at the end 26·16 grammes of nitrogen, 7·50 grammes of hydrogen, and 66·34 grammes of chlorine, the combined weight of these substances making up exactly 100 grammes. And in whatever way we perform the decomposition of sal ammoniac we always get these three substances and always in exactly the same proportions. By starting with nitrogen, hydrogen, and chlorine in the above proportions we can, of course, make sal ammoniac. And there is no way of making sal ammoniac except with just those proportions. No specimen of sal ammoniac ever has slightly more chlorine or nitrogen or slightly less hydrogen, for example, than any other specimen. The same remarks apply to every other compound. The general law may be enunciated thus: *the same compound is always formed of the same elements in exactly the same proportions.*

In the above example we obtained, in our preliminary dissociation of sal ammoniac, two substances each of which contained hydrogen. We obtained ammonia gas, which is made up of nitrogen and hydrogen, and we obtained

hydrochloric acid gas, which is made up of chlorine and hydrogen. We might ask the question whether there is any simple relation between the amount of nitrogen which combines with, say, one gramme of hydrogen, and the amount of chlorine which combines with one gramme of hydrogen. But before dealing with this question we will deal with another which has some bearing on it. Can two elements combine in different proportions to form different substances, and, if so, what is the relation between the proportions? The answer is that two substances can combine in different proportions to form different substances, but that, when this occurs, the proportions are simple multiples of one another. Thus, 3 grammes of carbon can unite with 8 grammes of oxygen to produce a substance called carbon dioxide. But 3 grammes of carbon can unite with 4 grammes of oxygen to produce a different substance called carbon monoxide. It will be noticed that the amount of oxygen in the first case is just twice that in the second. This example is typical. Whenever there is more than one compound of two elements the ratio

by weight of the elements in the two compounds is always a simple number. This fact is very suggestive, as we shall see.

We can now deal with our first question, and we can make it more general. Consider, for instance, hydrogen, oxygen, and carbon. We can take 2 grammes of hydrogen and combine them with 16 grammes of oxygen. The result is water. Again, if we take 16 grammes of oxygen and combine them with 12 grammes of carbon we shall obtain carbon monoxide. Here the 16 grammes of oxygen is the common factor. The appetite of this amount of oxygen for combination can be satisfied, apparently, either with 2 grammes of hydrogen or 12 grammes of carbon. And the interesting fact is that we can combine hydrogen and carbon in precisely this proportion. Two grammes of hydrogen combine with 12 grammes of carbon to form a substance called olefiant gas.

Now these are the facts that the atomic theory so beautifully explains. Let us see how it is done. Dalton's atomic theory is to the effect that every element is built up of small equal particles. These particles are indivisi-

ble in the sense that less than one of them cannot take part in any chemical reaction. They are called *atoms*. The smallest part of a compound substance is called a *molecule*. It is built up out of atoms of the elements which unite to form that compound, and it is the smallest part of the compound which can exist as that definite substance. If a molecule were split up we should simply get the constituent elements again; the compound substance itself would have ceased to exist. Consider, for instance, a molecule of carbon monoxide. We know that this molecule is formed from one atom of carbon and one atom of oxygen. We write it CO. The carbon dioxide molecule, on the other hand, is formed from one atom of carbon and two atoms of oxygen. We write it CO_2. A carbon dioxide molecule contains exactly twice as much oxygen as does a carbon monoxide molecule. It cannot possibly contain 1½ times as much or 1¾ times as much, since the amount of oxygen present in a molecule must vary by at least one atom. Thus we see how it is that the proportions are whole multiples.

The atomic theory gave so clear and simple an account of the laws of combination that there could be little doubt of its truth. The ordinary chemical methods, however, did not enable one to decide unambiguously what were the exact relative weights of the atoms of the different elements. This question is obviously of great importance, but the law discovered by Avogadro, called Avogadro's hypothesis, enabled the matter to be cleared up. This hypothesis asserts that *equal volumes of different gases, under the same conditions of temperature and pressure, contain equal numbers of molecules.* We may mention here that many elements normally exist in a molecular form, that is, their atoms unite together in twos or threes to form molecules.

§ 3. *Relative Weights of Atoms*

We will now give the reasoning by which, from Avogadro's hypothesis, the relative weights of atoms may be deduced. Suppose we have a number of precisely similar vessels, each having the same volume V, and each filled with

a gas at the same temperature and pressure. Then, according to Avogadro's hypothesis, they each contain the same number of molecules. Suppose we take two of these vessels, one containing hydrogen and the other oxygen, and compare the weights of the two quantities of gas. Since they have the same number of molecules, the relative weights of the two quantities of gas is the same as the relative weights of their molecules. But is this sufficient to determine the relative *atomic* weights of hydrogen and oxygen? Obviously not, for the molecule of hydrogen, for all we know, may contain two or more atoms, and so may the molecule of oxygen. This method will not give us the desired result.

But we have said that the atom is the smallest part of an element that takes part in any chemical combination. What we really mean by that is that the smallest part of an element which takes part in any known chemical reaction is called an atom. Suppose, therefore, we consider all the compounds into which hydrogen enters. Amongst these compounds there will be one whose molecules contain a mini-

mum amount of hydrogen. The molecules of this compound contain, therefore, one atom of hydrogen. The volume V of this compound, in the gaseous state, and at a certain pressure and temperature, contains a mass of hydrogen which can be measured. Call this mass H. Now, of all the oxygen compounds, select that compound which contains the minimum weight of oxygen. The molecules of this compound contain one atom of oxygen. The volume V of this compound, in the gaseous state, and at the same pressure and temperature as the hydrogen compound, has a known weight of oxygen. Call this mass O. Both the oxygen and the hydrogen compounds have the same number of molecules, by Avogadro's hypothesis. Corresponding to each molecule of the hydrogen compound is one atom of hydrogen, and corresponding to each molecule of the oxygen compound is one atom of oxygen. We have, therefore, the same number of atoms of hydrogen in the one vessel that we have of oxygen in the other. The ratio of the weights of the hydrogen and the oxygen—that is, the ratio of

H and *O*—is therefore the ratio of their atomic weights. By a similar process we find the relative atomic weights of other elements, carbon, chlorine, etc. For the purpose of comparing these relative weights, oxygen is taken as the standard, simply because oxygen occurs so frequently in chemical combinations. It is nearly 16 times heavier than hydrogen, the lightest atom. Its weight is therefore taken as *exactly* 16. Compared with this hydrogen is 1·008. On this standard carbon's atomic weight is 12, and chlorine 35·456.

It is evident, from Avogadro's hypothesis, that 1·008 grammes of hydrogen contain as many atoms as 16 grammes of oxygen or 12 grammes of carbon or 35·456 grammes of chlorine, and so on. The number of grammes of an element which is equal to its relative atomic weight is called a *gramme-atom* of the element. All gramme-atoms contain the same number of atoms. This number is known. It is 660,000 times a million billion. This is the number of atoms in 1 gramme of hydrogen, 12 grammes of carbon, 16 grammes of oxygen,

etc. The actual weight of an atom, therefore, is to be obtained by dividing its gramme-atom by this number.

§ 4. *Some Experimental Evidence*

The figure we have just given for the weight of an atom is evidently exceedingly minute. Such small quantities are, of course, altogether below the limits of observation. Nevertheless, there is a series of experiments which enables us to see that the ultimate particles of matter must be extremely minute. Gold-leaf, for instance, can be prepared of a thickness of one ten-thousandth of a millimetre. In this state, gold-leaf is transparent and transmits a greenish light. It cannot be beaten out more thinly merely because of the difficulty of manipulating such thin sheets without tearing them. It is certain, therefore, that the diameter of a gold atom is less than the thickness of one of these sheets, that is, is less than 10^{-5} cm. The weight of a cube of gold, having this length for the length of its side, would be 10^{-14} gramme. The hydrogen atom is about 200

times lighter than the gold atom. On this showing, therefore, the mass of a hydrogen atom is certainly less than $\frac{1}{2} \times 10^{-16}$ gramme. The study of thin films takes us very much further. The black spots so familiar to us on soap bubbles are the thinnest part of the soapy film. The blacker they are the thinner they are. The thickness of these extremely thin films can be measured, and is found to be about $4{\cdot}5 \times 10^{-7}$ cm. The films produced by letting oil drops spread on water are even thinner. Films no thicker than $1{\cdot}1 \times 10^{-7}$ cm. have been obtained. The maximum possible diameter for an oil molecule, therefore, would be about 1×10^{-7} cm. A hydrogen atom would weigh nearly a thousand times less than one of these oil molecules, and we can calculate, on this basis, that the mass of a hydrogen atom would be of the order of 10^{-24} gramme. The actual mass of a hydrogen atom, as can be shown by other calculations, is $1{\cdot}65 \times 10^{-24}$ gramme. By actual experiment, therefore, we can obtain films so thin that they are not much more than one molecule in thickness.

§ 5. *Molecular Movements*

If two liquids are taken and one is placed on top of the other, we know that they will begin to mix. In some cases the mixing process may take a long time and may seem to be incomplete, as when water and ether are superposed, for example. But even in this case we would find, after a time, that every part of the layer of ether contained some water, and that in every part of the water there was some ether. With most pairs of liquids the diffusion is more rapid and obvious. Even solids diffuse very slightly. With pairs of metals which have been kept in contact for years, it is found that the bottom layer of one and the top layer of the other have become, to some extent, intermingled. In the case of gases, diffusion is rapid and complete. Berthollet took a globe containing carbon dioxide, a heavy gas, and put it in communication by means of a stop-cock with another globe containing hydrogen, the lightest of gases. The globe of hydrogen was above the globe of carbon dioxide, and in each globe the gas was at the same pressure. When the stop-

cock was opened it was found that, after a little time, each globe contained as much carbon dioxide as hydrogen. With any pair of gases the result is the same.

This range of phenomena obviously points to the existence of molecular motions. We must imagine that each tiny particle of a liquid or a gas is in incessant movement. Even in the case of solids, there is some movement of the molecules, although here the movement is much more restricted. In a gas, in particular, the molecules must be moving about in all directions, perpetually colliding and changing their directions. A rise in temperature increases the velocity of these movements. All phenomena of diffusion take place at a greater rate the higher the temperature. What affects our senses as heat is, in fact, the energy due to these molecular movements. The hotter the body the greater the energy of motion of its molecules. Thus there is no such thing as a greatest possible temperature. The temperature of the outer layers of the sun is some thousands of degrees; the temperature of the innermost parts may be some millions of degrees.

But there is an absolute zero of temperature; no body can be colder than the absolute zero. As the temperature of a body decreases its molecular movements become feebler and feebler until, at a sufficiently low temperature, they cease altogether. This lowest possible temperature is the same for all bodies. It is —273° C.

The hypothesis that a gas consists of a large number of molecules moving about in all directions with all velocities is called the Kinetic Theory of Gases, and its mathematical development enabled us to account for the known laws of gases and to predict other phenomena which have since been observed. At first sight the problem appears to be a very complicated one. We have to assume that the molecules are moving at random; some are moving slowly, some fast, some very fast, and so on. They are moving in all directions; they are perpetually colliding. Their motions are completely chaotic. But this very fact, which seems to make the problem insoluble, was shown by James Clerk Maxwell to lead to its solution. If we imagine our gas to be enclosed in a box, for instance, then we may suppose

that some of the molecules, at a given instant, are moving towards one of the sides of the box with a certain velocity—say 100 yards per second. But besides having this motion, these molecules will also, in general, be moving towards a side at right angles to the first one and also, it may be, towards the floor or ceiling of the box. What do we know about these other motions from the fact that these molecules are moving towards one side at 100 yards per second? According to Maxwell, we know nothing whatever about these other motions. They might be anything. And from this mere fact he was able to deduce how different velocities are distributed amongst the molecules of the gas by applying the theory of probabilities. The pressure exerted by a gas is due to the incessant bombardment of its containing vessel by its molecules. At a given temperature there is a simple connection between the pressure and the volume of the same mass of gas. If the volume is halved the pressure is doubled; similarly, if the volume is doubled the pressure is halved. The general relation is that, at constant temperature, the volume multiplied by

the pressure is constant. In virtue of their motion, the molecules possess energy, and Maxwell showed that, for a given mass of gas, the product of the pressure and volume of that mass of gas is equal to two-thirds of the energy of translation of its molecules. At the same temperature, therefore, it does not matter whether the same mass of gas occupies a large volume or a small one; the energy due to its molecular motions is the same. This energy is considerable. If the molecular energy of 2 grammes of hydrogen could be utilised it would be sufficient to raise a weight of 350 kilogrammes through 1 metre. The speed of these flying molecules is very considerable. At the temperature of melting ice the average velocity of oxygen molecules is about 425 metres per second, which is nearly that of a rifle bullet. At the same temperature, the hydrogen molecule is moving four times as fast, namely, 1700 metres per second. These velocities are the average velocities. Some molecules are moving more slowly, and some faster. The molecules are constantly colliding. The average distance between successive collisions is called the mean

free path, and can be calculated. For air at normal temperature and pressure, the mean free path is about one ten-thousandth part of a millimetre. Collisions occur, therefore, about 5,000 million times a second.

§ 6. *The Brownian Movement*

We now come to a remarkable discovery which gives us actual visible evidence of the reality of these molecular movements. An English botanist named Brown, using the improved microscope objectives which had just been introduced, noticed, in 1827, that very small particles suspended in water were in a state of constant movement. This phenomenon was at first dismissed as being due to vibration or to convection currents in the water. More careful experiments showed that the motion certainly was not due to such causes. It does not occur only in water. It occurs in all fluids, although the more viscous the fluid the less active is the motion. The size of the small particles is an important factor—the smaller the particles the more lively the movement—

but the substance or density of the particles seems to be without effect. The movement never ceases. It has been observed in liquid which has been shut up in quartz for thousands of years.

These movements have been very thoroughly observed, under a variety of conditions, by Perrin, and their theory has been worked out by Einstein. The correspondence between theory and observation is remarkably satisfactory, and there can now be no doubt that the Brownian movement is a direct manifestation of the chaotic molecular movements of the fluid. We must imagine each small particle as being constantly bombarded by the molecules of the fluid surrounding it. If the particle be fairly large, these molecular impacts, occurring irregularly and on every side of the particle, cancel out. No resultant motion is given to the particle. But if the particle be small the chances are less that the irregular impacts will cancel out. It may happen that, for a time sufficient to produce visible motion in a very small particle, the majority of the impacts are in one direction. A moment after-

wards, of course, the direction has changed. So we get this incessant and extremely irregular motion called the Brownian movement. The way in which the agitation depends on the molecular energy of the fluid, on its viscosity, and on the dimensions of the particles has been worked out by Einstein, and his results have received experimental confirmation.

Chapter III: *Constituents of the Atom*

Chapter III

Constituents of the Atom

§ 1. *The Electron*

THE notion that matter consists of discrete particles is, as we have seen, a very satisfactory hypothesis. As opposed to the only other possible theory, that matter is continuous, the atomic theory is more successful in explaining phenomena, and it also appears to be a more natural theory, one more easily grasped. The "continuum" theory has had its supporters, however, amongst whom we may mention Goethe, besides the more serious scientific names of Mach and Ostwald. But whatever arguments there may once have been in favour of the continuous theory of matter, recent work has caused the theory to be irretrievably abandoned. But when we turn from matter to the "imponderables" such as light, heat, electricity, the case is rather different. Both heat and electricity were for a long time regarded as fluids.

These fluids were regarded as imponderable and continuous. There was even a two-fluid theory of electricity according to which the two kinds of electricity, positive and negative, were manifestations of two different fluids. According to the one-fluid theory, the two kinds of electricity were manifestations of the presence of a defect or excess of the fluid. But these theories, although occasionally written about at length, were rather perfunctory. They were little more than convenient mathematical fictions. By assuming them, the mathematicians were enabled to get on with their real interests, which consisted in working out the laws according to which electrified bodies acted on one another. The whole of this early work was purely formal. Experiment had shown that the fundamental law of electrostatics was of the same form as the Newtonian Law of Gravitation. Electrified bodies were regarded as geometrical shapes carrying electric "charges" and attracting or repelling one another according to the Newtonian law. "Action at a distance" was assumed; that is to say, the change of force between electrified bodies

which accompanied change of position was assumed to take place instantaneously, so that the positions and charges at a given instant gave the forces at that same instant. This was the same assumption that underlay the Newtonian Law of Gravitation, and it was open to the same objection, namely, that it made it very difficult to conceive how the action between distant bodies was propagated through the space separating them. If the notion of propagation were given up the mutual action between bodies not in contact became purely miraculous; if the notion of propagation were retained it had to be conceived as taking place with infinite velocity.

A very great advance on these conceptions was made by James Clerk Maxwell. He directed attention to the "field," to the space separating electrified bodies, and he established mathematical equations whereby the propagation of electric and magnetic actions in space could be followed from point to point and from instant to instant. And he showed that electromagnetic effects were propagated with the velocity of light, *i. e.*, 300,000 kilometres

per second. Light itself was shown to be an electromagnetic phenomenon, and hence the theory is usually called the Electromagnetic Theory of Light. Heinrich Hertz, a brilliant follower of Maxwell, succeeded in producing electromagnetic waves some metres in length, and in showing that they could be reflected and refracted and made to behave generally in ways characteristic of light waves. Wireless telegraphy was developed directly from Hertz's work, and electromagnetic waves were produced several kilometres in length. Thus the very important transition was made from the action of a distance-theory to the field-theory of electric and magnetic action.

In the meantime, the study of the electric charges themselves had been comparatively neglected. Certain phenomena attending the conduction of electricity in solutions had, it is true, given rise to speculations that electricity was probably atomic in constitution, but it was not until the so-called cathode rays were studied that the existence of atoms of electricity, disconnected from ordinary matter, was experimentally confirmed. The apparatus nec-

essary to produce cathode rays consists of a glass tube in which an almost complete vacuum exists. Through the walls of this tube two metallic wires are passed, which are connected to a source generating electricity. One of these wires is terminated, on the inside of the tube, by a metallic disc. If now the potential difference between the two wires is sufficiently high (some hundreds of volts) rays emanate from the metallic disc (called the cathode) and proceed in straight lines, producing a fluorescence at the other end of the tube where they strike the glass walls. That the rays proceed in perfectly straight lines may be shown by placing an object in the path of the rays—say a cross or a circular disc—when its clear-cut shadow is thrown on the far end of the tube.

Now the fact that these rays are deflected when the tube is placed in an electric or magnetic field shows that they consist of small electrified particles in movement. Further, the nature of the deflection shows that the electric charges carried by these small particles are charges of negative electricity. The question arises: What is the nature of the small electri-

fied particles? Are they, for instance, atoms of matter carrying electric charges? Are they, perhaps, larger than atoms? Can it be that they are smaller than atoms, that in the cathode rays we have matter existing in a sub-atomic state? Certain measurements were made which allowed this question to be answered without ambiguity. Each little electrified particle or corpuscle carried a charge e and had a mass m. The measurements did not determine either e or m directly, but they did determine the ratio e/m of these two quantities. The ratio turned out to have the extraordinary value of $1{\cdot}77 \times 10^7$ (electromagnetic) units. Let us see just why this value was so extraordinary.

If X-rays or the rays emitted by radium are allowed to penetrate a gas, they have the power of enabling that gas to conduct electricity. The rays, in their passage through the gas, produce positively and negatively charged carriers of electricity. These carriers are called Ions. Now the most important characteristic of an ion is its electric charge, and an ingenious experimental method enables this charge

to be determined. If air be saturated with water vapour and the air be then suddenly expanded, the resultant cooling causes a cloud of small drops of water to be formed. These drops coalesce round the tiny dust particles present in the air. If the air has been purified of dust particles it is possible for a considerable expansion to take place without the formation of a cloud of drops. It was found, however, that if ions are present they play the part of dust particles. Small drops condense round the ions and a cloud is formed. By taking suitable precautions, a single drop can be observed under the microscope. These drops fall under their own weight. Now the rate of fall of such a drop will depend on its size, its density, and on certain properties of the gas through which it is falling. The mathematical problem of determining the velocity of the drop from these other factors was solved by Sir George Stokes. Now when the drops are formed round the little electrified bodies called ions each drop carries an electric charge. If, therefore, we cause an electric force to act on the drop, say by letting the drop fall between two parallel electri-

fied plates, we can cause the electric force to act either with or against the gravity of the drop and so either hasten or retard its descent. Knowing the rate of fall under gravity alone, and also the rate of fall under a known electric force, the actual charge carried by the drop can be calculated. In this way it was found that the smallest charge, the charge carried by a single ion, is $4 \cdot 77 \times 10^{-10}$ (electrostatic) units. Now the ion, besides having a charge has also, of course, a certain mass. The lightest ion known, the hydrogen-ion, which consists of a single hydrogen atom carrying the above charge, has for the ratio e/m, the ratio of charge to mass, the value $9649 \cdot 4$ (electromagnetic) units. Let us contrast this with the ratio $1 \cdot 77 \times 10^{7}$ obtained for the electrified corpuscles of the vacuum tube. This latter value is more than 1800 times greater than the value for the hydrogen-ion. How is this to be explained?

We might suppose that each electrified corpuscle is an atom carrying a great many of the elementary electric charges—*i. e.*, the smallest charge carried by a single ion. But if we sup-

pose the corpuscles to be single atoms on which many charges are heaped, we should hardly expect the ration e/m to be always the same for every corpuscle. It would seem that there ought sometimes to be more and sometimes fewer charges. But a grave objection is that the ratio e/m for the corpuscles is quite independent of the nature of the gas of which a residuum is always left in the vacuum tube, and is quite independent of the material constituting the cathode. If the corpuscles are electrified atoms, where do these atoms come from? Atoms of different substances have different weights. How, then, does it happen that the ratio e/m always remains the same? The only possible hypothesis which explains all the facts is that the corpuscles consist of elementary charges of electricity linked to a mass about 1800 times smaller than the mass of a hydrogen atom. The corpuscles are of sub-atomic dimensions. These tiny particles are called Electrons.

Of the existence of these bodies there can no longer be any doubt. A great number and variety of phenomena are now known which

point to their existence; electric currents, radioactive processes, the generation of X-rays, various optical effects, all bear witness to the existence of these sub-atomic electrified bodies. Precise measurements enable us to give the mass of an electron. It is $0{\cdot}903 \times 10^{-27}$ gramme. As a comparison, we give also the mass of a hydrogen atom, which is $1{\cdot}650 \times 10^{-24}$ gramme, a value about 1830 times greater than that of the electron. The figure giving the mass of an electron may be expressed by saying that one thousand million million million million million electrons would have a mass rather less than one gramme.

But the mass of an electron, although so small, is not zero. What are we to suppose are the origin and nature of this mass? Here we are led to a very startling and novel conception. We have always supposed that only matter had mass; electricity has been classed as an "imponderable," that is, as something possessing no mass. But this notion cannot be maintained. An electric current in a wire, for instance, is produced by the application of an electromotive force, but the current does not

attain its full strength *instantly* when the force is applied. Similarly, when the force generating the current is suppressed the current does not instantly vanish. It shows a tendency to persist. It seems to be endowed with inertia, and inertia is a property of mass. Further, Sir J. J. Thomson showed that an electrified material sphere requires a greater force to set it in motion than if it were unelectrified. The electric charge acted as if it imparted some extra mass to the sphere. Part of the mass of the sphere could be attributed to its ordinary matter and part to its electric charge. If we regard our electrons, therefore, as small electrified spheres, how much of their mass is to be referred to their electric charge? We reach the startling conclusion that the *whole* of the mass of an electron is to be attributed to its electric charge. This conclusion, we must mention, is not absolutely proved. It is a very convenient and plausible assumption to make, however, and leads to a very simple conception of matter. We shall see that all atoms may be conceived as built up out of electrons, and since electrons consist of nothing but electricity, we see that

we reach an electric theory of matter, where matter is held to consist of nothing but electric charges, and to have no mass except the mass that results from these charges.

The initial difficulty of this conception resides wholly in its unfamiliarity. When we become accustomed to the idea of attributing mass to an electric charge, we shall find that it has thereby acquired just the "materiality" necessary for it to figure as what we mean by matter. On the hypothesis that the mass of an electron is due wholly to its electric charge we find, assuming the electron to be a sphere, that its radius is approximately 2×10^{-13} cm., or two ten million-millionths of a centimetre. This is about 50,000 times smaller than the radius of an atom. As compared with an atom, an electron would be like a fly in a cathedral, to use Sir Oliver Lodge's vivid image.

Although we have said that matter is built up out of electrons, we cannot suppose it to consist of nothing but such negatively electrified corpuscles as are produced in a vacuum tube. Ordinary matter is electrically neutral; it does not exist in a state of permanent nega-

tive electrification. These negative charges must therefore be somehow associated with exactly compensatory positive charges. Now the elementary positive charge of electricity, which is of the same magnitude as the elementary negative charge, is never found associated with a smaller mass than that of the hydrogen atom. The hydrogen-ion carries the same positive charge that the electron carries negative charge, but that positive charge is never found in a "dissociated" state. We shall find, indeed, that the elementary positive charge plays quite a different *rôle* in the constitution of matter from that played by the negatively charged electron.

§ 2. *Radium*

The theory we are introducing, that atoms of matter are built up out of electric charges, is magnificently illustrated by the phenomena of radioactivity. It was in 1896 that the French scientist Becquerel found that uranium salts spontaneously emitted a radiation which could, to some extent, pass through matter, whether transparent or opaque, could influence

a photographic plate, and could make air and other gases conductors of electricity. Further investigation showed that other substances also had the power of emitting these radiations, and some of them, such as Radium, possessed this property in an extraordinary degree. About forty radioactive substances are known at the present day.

The question arises, What is the nature of these radiations? To answer this question the method of analysis was adopted that we have already mentioned. The radiations, if they consist of electrically charged particles, will be deflected both by a magnetic and by an electric field. Each of these deflections gives us some information about the ratio e/m of the charge to the mass of the particles, and also about the velocity V with which the particles are moving. From the information supplied by the two sets of deflections we can determine these two quantities, *i. e.*, we can find e/m and also V. When this method of analysis was applied it was found that the radiations from radium consisted of three kinds of rays having entirely different properties. These three types are called

α–, β–, and γ-rays. The γ-rays continued without deflection; it became apparent that they did not consist of electrically charged particles at all. The β-rays proved to be negatively charged, and the amounts of the electric and magnetic deflections proved that they were of exactly the same type as the streams of electrons in a vacuum tube. The α-rays behaved very differently. They turned out to be positively instead of negatively charged, and also to possess much greater masses than the β-rays. It was found that the ratio e/m for an α-particle was the same for all α-particles, from whatever radioactive substance they were obtained. This value was found to be 4823 (electromagnetic) units. Now this value is one-half the value of the ratio e/m of a hydrogen-ion. How is this to be explained? There are three possibilities. We might say that the α-particle carries a unit positive charge, the same as the hydrogen-ion, but that this charge is united with *two* hydrogen atoms. Or we might say that it has a unit positive charge, but attached to the atom of a new element which has twice the mass of a hydrogen atom. The

other possibility supposes that we are dealing with a helium instead of with a hydrogen atom. Now the atomic weight of helium is 4, *i. e.*, an atom of helium has four times the mass of an atom of hydrogen. If, therefore, we assume that an α-particle is an atom of helium, we must suppose it to be carrying two unit positive charges. To distinguish between these possibilities, it obviously becomes necessary to measure the actual charge carried by an α-particle. This was done by direct experiment. The number of α-particles emitted from a source can be counted directly, and the total charge they carry can also be measured. The charge carried by a single particle can thus be determined. Its value proved to be twice the value of the unit charge. The hypothesis, therefore, that an α-particle consists of a helium atom carrying two units of positive charge is justified by experiment. Thus we see that radioactive elements can emit positively charged helium atoms. This conclusion was directly confirmed by Rutherford and Royds, who collected α-particles in an evacuated space, and, on causing an electric discharge

to pass, obtained the spectrum of helium.

The α-particles are easily absorbed in their passage through matter. They can be stopped by an ordinary sheet of writing-paper. The velocity of the α-particles varies with the nature of the radioactive substance which emits them, but, speaking approximately, we may say that their velocity is about 2×10^9 centimetres per second. This is much less than the velocity of light, which is about 3×10^{10} centimetres per second.

The β-particles, on the other hand, sometimes have a velocity which is within one per cent. of that of light itself. It is evident that the radioactive process, whatever it may be, must be tremendously energetic to produce these high velocities. But although, on the average, the velocity of a β-particle is ten times that of an α-particle, the latter, owing to its greater mass, has greater momentum and energy. The β-particle, in its passage through matter, is readily deflected, and is sometimes deflected through a very considerable angle. It may, in fact, be turned so much out of its path as to emerge again on the same side that

it entered. For this reason, it is difficult to say just what penetrative power the β-radiations have, but we may say, roughly, that they are about 100 times as penetrating as α-rays.

The γ-rays, as we have said, do not consist of electrified particles at all. They have the character of extremely minute light-waves, although they do not, of course, cause visibility. They always accompany the emission of β-particles from radioactive substances and their penetrative powers are considerable, being about 100 times greater than those of the β-rays. We shall learn more of their properties in the section discussing X-rays.

Now what are we to suppose is happening during these radioactive processes, attended, as they are, by so great an expenditure of energy? The theory now universally accepted is that the atoms of a substance manifesting radioactivity are actually disintegrating. The atoms of such substances are unstable and are breaking up. The electrified particles, the α- and the β-rays, are shot out by the atom in its process of disruption. This process of disruption cannot be hastened or retarded by any artifi-

cial means. It takes place, for a given substance, at the same rate whether the temperature be that of liquid air or of red-hot iron. The atom, on breaking up, becomes transformed into a different atom, having a different atomic weight. The second atom may be, in its turn, unstable, and disintegrate into yet another atom. In this way, before a disrupting atom settles down into a stable condition, it may pass through quite a long series of states —transforming itself from one substance into another. Thus uranium, with an atomic weight of 238, passes through a long series of changes to reach stability finally as lead, with an atomic weight of 206. This fact has led to a method of determining the ages of some uranium minerals. The amount of lead produced by a known weight of uranium in a given time can be determined, and the examination of the amount of lead present in a uranium mineral enables a maximum age for the mineral to be calculated. The assumption is that the lead present in the mineral has resulted from the transformations of the uranium. In this way a mineral of the Carboniferous period has been

found to have an age of 340 million years, and a pre-Cambrian mineral to have an age of 1640 million years. We have seen, also, that the α-particles expelled during some radioactive processes are really helium atoms. Now helium is only found in large quantities in old minerals rich in uranium or thorium (another radioactive substance), and if the helium be supposed to have resulted from the disintegration of these substances the age of the mineral can be calculated. But this value will be a minimum value of the age of the mineral, since we must suppose that some of the gas has been lost. In this way figures have been obtained for different geological strata ranging from 8 million to 700 million years.

§ 3. X-*rays*

It was in 1895 that Röntgen discovered that invisible radiations of some kind passed through the cathode tube and that these radiations had great penetrative power.

He discovered that many substances, opaque to ordinary light, are transparent to these *X*-

rays, as they were called. The rays arose at the point where the stream of electrons within the tube struck the glass walls, and radiated from these points of impact in all directions. Ordinary deflection experiments showed that the X-rays did not consist of electrified particles, but were a form of wave motion. Now there are two forms of wave motion, *longitudinal* and *transversal.* If a rope, held by the hand at one end and permanently fastened at the other, be shaken, a wave motion is propagated along it. The peculiarity of this motion is that each point of the rope, as the disturbance reaches it, moves in a direction at right angles to the direction of propagation of the wave. Such a wave motion is said to be transversal. The wave motion which constitutes ordinary light is known to be of this character. But there is another form of wave motion where each point of the medium set in motion moves to and fro in the direction of propagation of the wave. Sound consists of waves of this type. Such waves are called longitudinal. The question arose whether the waves constituting X-rays were longitudinal or transverse. It was

not till ten years later that this point was definitely settled, and it was shown that *X*-rays, like ordinary light, consist of transverse waves, but waves which are, compared with light-waves, of exceedingly small wave-length. The waves constituting *X*-rays are about 10,000 times smaller than those constituting ordinary light. It is this extraordinarily small wave-length that gives them their great penetrative power. Not all *X*-rays have the same wave-length; their wave-length depends on the manner in which they are generated. The shorter the wave-length the greater the penetrative power or "hardness" of the rays.

We have said that *X*-rays are produced by the sudden stoppage of the electrons on striking the wall of a cathode tube. The sudden alteration in velocity creates the wave disturbance called *X*-rays, and the greater the velocity of the electrons the greater is the "hardness" or penetrative power of the resultant waves. In modern cathode tubes, it is usual, instead of allowing the stream of electrons to strike the glass tube, to direct the stream on to a piece of metal having a high

melting point, such as platinum. This piece of metal, which receives the impact of the electrons, is called the anti-cathode. Now the very important discovery was made that the *X*-rays which result from the bombardment of the anti-cathode are of two kinds. The first kind is due merely to the stoppage of the electrons, as we have seen. But besides these, the anti-cathode, under the influence of the bombardment, sends out *X*-rays of its own. This second group of *X*-rays is of particular wave-lengths, the same for the same substance, but different for different substances. The *X*-rays so emitted are, in fact, entirely characteristic of the substance that emits them. For a given element these *X*-rays remain the same whether the element is isolated or whether it is in chemical combination with others. It is evident, therefore, that these *X*-rays manifest some property which belongs to the *atoms* of the element. If we compare the *X*-rays characteristic of elements of different atomic weights we find that the heavier the atom the shorter the wave-lengths of the characteristic *X*-rays. The "hardness" of the *X*-rays proper to an element

increases as the atomic weight of the element increases. We shall find that this group of X-rays, those proper to the substance itself, throws much light on the structure of the atom.

The γ-rays, emitted by radioactive substances, resemble X-rays in being waves of very small wave-length and consequently great penetrative power. They are much smaller even than X-rays, for γ-rays can be obtained about twenty times smaller even than the hardest X-rays. But that they are essentially similar to X-rays there can be no doubt, and it must be supposed that they have a similar origin. We have seen that X-rays are produced by sudden alterations in the velocity of a moving electron. We have also seen that the β-rays of radioactive substances are electrons moving with very high velocities, and we have further noted that γ-rays always attend the expulsion of β-rays. It is very reasonable to suppose, therefore, that the γ-rays are produced by the β-rays in their escape from the atom. But we cannot go into this matter more closely until we know more about the constitution of the atom.

CHAPTER IV: *The Structure of the Atom*

Chapter IV

The Structure of the Atom

§ 1. *The Order of the Elements*

WE have already said that the various chemical elements are not entirely unrelated to one another. The different chemical elements fall naturally into groups, the members of each group greatly resembling one another in their chemical properties. This fact particularly excited the attention of an Englishman named Newlands, who, in 1864, tried to show that the chemical elements fell into sets of seven, analogous to "octaves" in music. The subsequent discovery of other elements, however, made this scheme unsatisfactory, and the first really convincing attempt at arranging the elements in this way was made by the Russian chemist Mendeléev about 1870. In this "periodic system," as it is called, the elements are arranged in the order of their atomic weights, beginning with hydrogen and ending with uranium. If we now number the elements

in the order of their atomic weights we find a curious and interesting relation between the members of the elements which have similar chemical properties. Elements numbered 3, 11, and 19 have similar properties. Elements 4, 12, and 20 have similar properties. The properties of 5, 13, and 21 are similar; so are those of 6, 14, and 22. And so on. We see that, for the elements belonging to the same group, their numbers succeed one another by the same amount, viz., 8. Thus $11 - 3 = 19 - 11 = 8$, and $12 - 4 = 20 - 12 = 8$, and so on. It is as if approximately the same set of chemical properties belonged to each eighth member of the table.

But the matter is not really as simple as this. The rule works well enough provided we confine our attention to the earlier part of the table, *i. e.*, to the elements having comparatively low atomic weights. As we go farther on in the table we find the recurrence of chemical properties begins after the *eighteenth* instead of the eighth member, and, still later on, we have a group of no less than thirty-two elements having different chemical properties.

These facts are clearly represented in the following table, where the lines join elements having similar properties.

It will be noticed that the table of the elements terminates with a row containing six members, the last of which is uranium. Uranium, as we know, is not a stable substance; it is disintegrating, and it is probable that no elements heavier than uranium are met with, not because they are theoretically impossible, but because they would be too unstable to survive.

We have seen that, neglecting the last six elements, all the other elements may be arranged in rows in the following way: One row of two elements, two rows of eight elements, two rows of eighteen elements, and one row of thirty-two elements.

Two points must be mentioned about the periodic table as we have represented it. In the first place, we have left spaces for five elements which have not yet been discovered, but whose properties and places in the table can be predicted. Such predictions have been made before, and the elements, when discovered, have completely verified the predictions. In

ARRANGEMENT OF THE ELEMENTS IN GROUPS IN ORDER OF THEIR ATOMIC NUMBERS

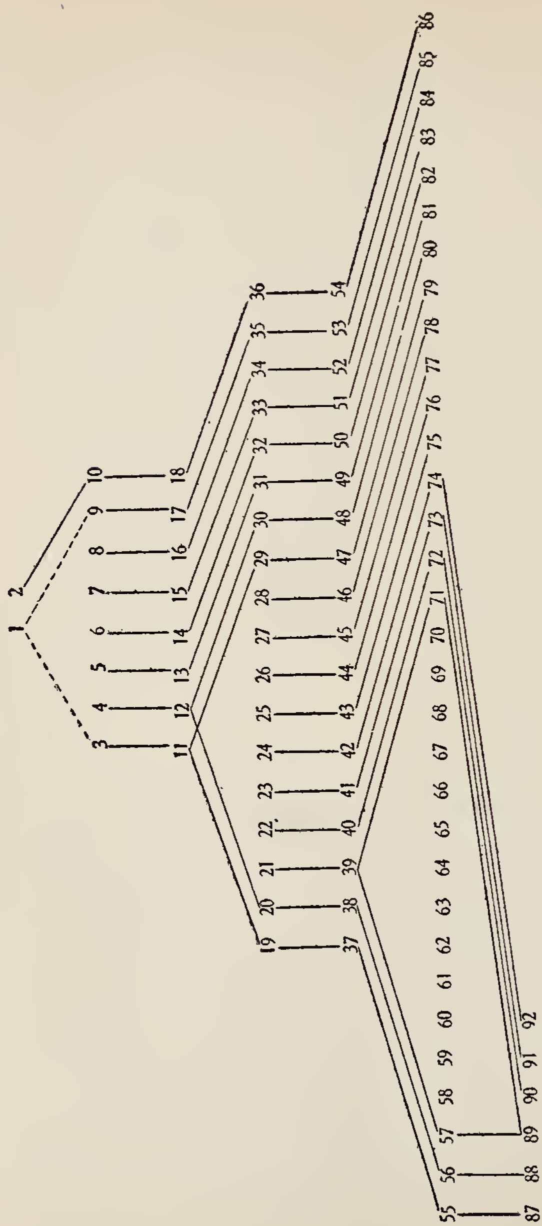

Table showing the groups in the Periodic System and which elements are related to one another in the different groups

NAMES OF ELEMENTS AND THEIR ATOMIC WEIGHTS ARRANGED IN ORDER OF THEIR ATOMIC NUMBERS.

No.	Name	Weight	No.	Name	Weight
1.	Hydrogen	1·008	47.	Silver	107·88
2.	Helium	4	48.	Cadmium	112·4
3.	Lithium	6·94	49.	Indium	114·8
4.	Beryllium	9·1	50.	Tin	118·7
5.	Boron	10·9	51.	Antimony	120·1
6.	Carbon	12	52.	Tellurium	127·5
7.	Nitrogen	14·01	53.	Iodine	126·92
8.	Oxygen	16	54.	Xenon	130·2
9.	Fluorine	19	55.	Cæsium	132·8
10.	Neon	20·2	56.	Barium	137·37
11.	Sodium	23	57.	Lanthanum	139
12.	Magnesium	24·3	58.	Cerium	140·2
13.	Aluminium	27·1	59.	Praseodymium	140·6
14.	Silicon	28·3	60.	Neodymium	144·3
15.	Phosphorus	31	61.	Unknown	—
16.	Sulphur	32·06	62.	Samarium	150·4
17.	Chlorine	35·456	63.	Europium	152
18.	Argon	39·9	64.	Gadolinium	157·3
19.	Potassium	39·1	65.	Terbium	159·2
20.	Calcium	40·07	66.	Dysprosium	162·5
21.	Scandium	44·5	67.	Holmium	163·5
22.	Titanium	48·1	68.	Erbium	167·7
23.	Vanadium	51	69.	Thulium	168·5
24.	Chromium	52	70.	Neoytterbium	172
25.	Manganese	55	71.	Lutecium	174
26.	Iron	55·8	72.	Hafnium	—
27.	Cobalt	58·97	73.	Tantalum	181
28.	Nickel	58·68	74.	Tungsten	184
29.	Copper	63·6	75.	Unknown	—
30.	Zinc	65·4	76.	Osmium	191
31.	Gallium	70·1	77.	Iridium	193·1
32.	Germanium	72·5	78.	Platinum	195
33.	Arsenic	74·96	79.	Gold	197·2
34.	Selenium	79·2	80.	Mercury	200·5
35.	Bromine	79·9	81.	Thallium	204
36.	Krypton	82·9	82.	Lead	207·2
37.	Rubidium	85·45	83.	Bismuth	208
38.	Strontium	87·63	84.	Polonium	210
39.	Yttrium	88·7	85.	Unknown	—
40.	Zirconium	90·6	86.	Niton	222
41.	Niobium	93·5	87.	Unknown	—
42.	Molybdenum	90	88.	Radium	226·4
43.	Unknown	—	89.	Actinium	(226-227)
44.	Ruthenium	101·7	90.	Thorium	232·1
45.	Rhodium	102·9	91.	Protoactinium	—
46.	Palladium	106·7	92.	Uranium	238·5

the second place, we have not, at every place in the table, adhered to the order of the atomic weights. There are four places where a heavier element has been put before a lighter one. In such cases we allow the whole complex of the chemical properties of the element, considered as a whole, to outweigh the considerations based only on its atomic weight. In the table as now arranged each element, including the five undiscovered elements, receives a number corresponding to its position in the table. These numbers range from 1 to 92, and they are called the *atomic numbers* of the elements. The atomic number of an element is, in the light of the new theories, a more fundamental and important characteristic than the *atomic weight* of the element. There is obviously a close connection between the atomic number and the atomic weight of an element, for the order of the atomic weights is almost exactly the same as the order of the atomic numbers and, further, the atomic weight of an element is, for the early part of the table, approximately twice its atomic number, excepting, of course, hydrogen, the first member of the table.

This latter property, that the atomic weight is twice the atomic number, is truer for the first part of the table than for the latter part. As we proceed along the table the atomic weights seem to depend less and less directly on the atomic number. It is obvious that we are not dealing with a case of simple proportionality, but that the atomic weight is, in reality, a quite complicated function of the atomic number.

The fact that the periodic classification of the elements is possible, that is to say, the fact that elements having different atomic weights can be arranged in groups because of the similarity of their physical and chemical properties lends great support to the theory that an atom is not a single, simple entity. There must be some similarity between the atoms of similar elements, and it is difficult to see what this similarity can be unless it be a similarity of structure.

§ 2. *The Atom as a Planetary System*

It is time now that we began to consider what sort of structure the atom may be sup-

posed to possess. We have seen that the discovery of electrons, and the phenomena of radioactivity, lead us to suppose that electrons somehow form part of the constitution of the atom. We have seen further that, since atoms are electrically neutral, we must suppose the electrons to be associated with an equal positive charge. How are we to suppose the electrons and the positive charge to be distributed? We shall see that certain experimental results lead us to adopt a planetary configuration for the atom. The positive charge is imagined as placed at the centre of the system, and circulating round it are a number of electrons sufficient to balance its charge exactly. The simplest conceivable case is of a unit positive charge, and one electron circulating round it. The distance of the electron from the positive charge would be, of course, the radius of the atom. It is supposed that the hydrogen atom is built up in just this way, namely, that it consists of a nucleus containing one positive unit of charge and, circulating round this nucleus, one electron. Such a conception is extremely simple, but before it can be considered as satis-

factory we must make it more definite. We have seen that an electron has a mass which is only $1/1800$ part of that of a hydrogen atom. If there is only one electron in a hydrogen atom, therefore, we must imagine that practically the whole mass of the atom is concentrated in its positive nucleus. Besides the fact, therefore, that the ultimate positive charge, the nucleus, has an equal and opposite electrical charge to that of the ultimate negative charge, the electron, we must imagine that it is about 1800 times more massive than the electron. The nucleus, deprived of its electron, would still behave, so far as mass is concerned, like a complete hydrogen atom. But it would behave like a hydrogen atom carrying one unit of positive charge. Such atoms are known. Heavier atoms, containing several electrons surrounding a nucleus having several positive units of charge, could conceivably lose one, two, three, four, or more electrons and consequently manifest as an atom carrying one, two, three four, or more positive charges. But it would be impossible, if our simple picture is right, for the hydrogen atom ever to manifest more

than one positive unit of charge. And, in fact, no hydrogen atom has ever been discovered which does manifest more than one positive unit of charge, although heavier atoms have been found which manifest several positive charges.

The element that follows on hydrogen in the order of atomic numbers is helium, and the simplest hypothesis to make concerning the structure of the helium atom is that it consists of a nucleus containing two positive charges and, circulating round it, two electrons. How these two electrons are supposed to be arranged is a problem of some difficulty. The most obvious idea would be to suppose that they were at opposite ends of a diameter and moving round the nucleus in the same circle. But there are reasons for thinking that this picture cannot be true. We shall take up this question later when we come to consider the general group of problems relating to the distribution of electrons within atoms. But, however they may be arranged, we suppose the helium atom to consist of two electrons circulating round a

nucleus containing two positive charges. Now, if this picture is correct, we cannot simply suppose the helium nucleus to be composed of two hydrogen nuclei. It is true that this would give two positive charges for the nucleus, but the weight of the nucleus would be wrong. The atomic weight of helium is not 2, but 4, and we have seen that practically the whole mass of an atom is concentrated in its nucleus. Since the nucleus of a helium atom has four times the mass of a hydrogen atom, it follows that the helium nucleus must contain no less than four hydrogen nuclei. Yet its charge is only two positive units. How is this to be accounted for? We can only account for it by giving the nucleus itself a rather complicated structure. We must imagine that the helium *nucleus*, besides containing four hydrogen nuclei, contains also two electrons. The charge of these two electrons neutralises the charge of two of the hydrogen nuclei and leaves, for the resultant positive charge of the helium nucleus, two units. Thus we see that, if we are to consider all atoms as built up out of hydrogen

nuclei and electrons, it cannot be done by simply adding hydrogen nuclei together in order to produce the nucleus of another atom.

The principle is, we see, simple. The number of hydrogen nuclei which go to make up the nucleus of an atom must be equal to the atomic weight of that atom, since it is from the hydrogen nuclei that the atom acquires its weight. The resultant positive charge on the nucleus, however, is equal to the *atomic number* of the atom. An atom of gold, for instance, has a mass of 197. Its atomic number is 79. Its nucleus consists, therefore, of 197 hydrogen nuclei and 118 electrons, since $197 - 118 = 79$, and the resultant positive charge on the nucleus is 79. To balance this resultant positive charge of 79 there are 79 electrons circulating round the nucleus. It is this resultant positive charge, and the electrons circulating round it, which determine the physical and chemical properties of the atom. The actual mass of the atom affects these properties only to a very small degree. It is for that reason that it is not the atomic weight, but the atomic number, which is the fundamental characteristic of an atom. It

is obvious, for instance, that we might obtain the same resultant positive charge with quite a different atomic weight. In the gold atom we get a charge of 79 by combining 197 hydrogen nuclei with 118 electrons. But if we had taken 198 hydrogen nuclei and 119 electrons we should have had an atom of different atomic weight, viz., 198 instead of 197, but of equal charge, namely, 79, and therefore of the same properties. We shall see that such variations in atoms exist, *i. e.*, we can have atoms of the *same substance* but of different weights.

Our picture of the helium atom is perfectly compatible with the fact that the α-particles shot out by radium are found to consist of helium atoms each of which carries two positive units of charge. Each α-particle is, in fact, a helium atom which has lost both its circulating electrons and which manifests, in consequence, two positive charges. In the same way that a hydrogen atom could not manifest more than one unit of positive charge, so a helium atom cannot possibly manifest more than two units of positive charge. But it is perfectly possible for a helium atom to lose only one of its two

electrons and therefore to manifest only one unit of positive charge. Such atoms are known to exist, whereas a helium atom carrying more than two positive charges has never been discovered.

Of the next element, lithium, we need only say briefly that its nucleus carries three positive charges and that, circulating round the nucleus, are three electrons. The lithium atom which has lost one electron, and consequently manifests one positive charge, is known, but the lithium atom which is minus two electrons has not yet been experimentally obtained.

Each step along the periodic table corresponds to the increase of the resultant charge on the nucleus by one positive unit and, consequently, to the addition of one electron to the circulating planetary system. By the time we get to uranium we have an atom which has 92 electrons in its planetary system, circulating round a nucleus containing a resultant positive charge of 92 units. Such a system is enormously complex. The complete mathematical treatment of such systems would lead to the elaboration of what is, at present, the practi-

cally non-existent science of mathematical chemistry. But the mathematical difficulties are enormous. They depend not only on the large number of "planets" which have to be treated, but on the peculiar difficulties offered by the very extraordinary nature of the laws which govern their motion. The further treatment of this point, also, we must leave till later.

§ 3. *Experimental Evidence*

When the α-particles from radium are passed through matter they suffer a certain amount of dispersion. In passing through a thin sheet of metal, for instance, the α-particles are deviated from the straight line they were pursuing when they encountered the metal. The amount of the deviation varies from one α-particle to another, but, on the whole, the deviations are very similar to those of shots round a target. The cause of these deviations must be sought in the encounters between the α-particles and the atoms of the metal. The α-particles are, as we have seen, the positively charged nuclei of

helium atoms. In passing through the metal sheet they will sometimes pass near or even through a metallic atom and experience a deflection due to the attraction of the electrons of that atom. It may be that a number of such encounters will happen to deflect the α-particle in the same direction, so that the resultant deflection may be considerable. But the chances of this can be worked out, and we reach the interesting conclusion that some of the observed enormous deflections which α-particles occasionally experience cannot be explained by any such cumulative effects. Deflections of 150°, *i. e.*, an almost complete reversal of direction, have been observed. It is true that such large deflections are not numerous (on passing through platinum, for instance, about 1 in 8000 α-particles are so affected), but the theory of successive small deviations cannot explain them. Also, the path of an α-particle through air can, in certain circumstances, actually be photographed, and the photographed path sometimes exhibits extremely abrupt changes of direction. Suddenly to deflect the massive α-particle, travelling at about 20,000 miles a

second, requires an intense force. It is necessary, therefore, to consider where these intense forces could come from.

As a result of measurements of the deflections of α-particles, moving with various velocities through different substances, Rutherford came to the conclusion that the abnormal deflections were produced when an α-particle happened to approach very closely to the nucleus of an atom. To account for the observed results it was necessary to suppose that the charge on the nucleus was concentrated within a very small region. An α-particle which approached sufficiently close to this highly concentrated positive charge would experience an intense repulsive force, and would be deflected in a hyperbolic path. The deflections enabled the actual positive charges carried by the nuclei of the atoms of the different metals to be calculated, and also the maximum value for the size of these nuclei. The charge was found to be greater the greater the atomic weight of the metallic atom and to be, within the limits of experimental error, equal to the atomic number of the atom. Thus, the experimental values for

platinum, silver, and copper were found to be 77·4, 46·3, and 29·3 respectively. The atomic numbers are 78, 47, and 29, and these figures agree with the experimental figures to within the limits of experimental error. Thus we have an experimental demonstration of the important law that the positive charge on the nucleus of an atom is equal to the atomic number of that atom. The experiments also showed that the maximum size that can be attributed to the nucleus of an atom is exceedingly small. Like the electron, the nucleus of an atom is very much smaller than an atom; it is of subatomic dimensions. There is reason to suppose, indeed, that the hydrogen nucleus is small compared even with an electron. It is probable that the radius of a hydrogen nucleus is not greater than 10^{-16} cm., which is about $\frac{1}{2000}$ part of the radius of an electron.

One of the most interesting and striking confirmations of our general theory is provided by radioactive phenomena. We have said that there are about 40 radioactive substances known, and they are all substances having high atomic weights. The nuclei of such heavy

atoms must be very complicated structures, built up, as the gold atom is built up, of a large number of hydrogen nuclei and several electrons. Now a radioactive substance, in the course of its disintegration, may give rise to several substances. Thus radium, in the course of disintegrating, gives rise to the following substances:—It produces Radium Emanation, Radium-*A*, Radium-*B*, Radium-*C*, Radium-*C′*, Radium-*C″*, Radium-*D*, Radium-*E*, Radium-*F*, Radium-*G*. Radium-*F* is polonium and Radium-*G* is lead. Two kinds of particles are shot out during this series of disintegrations, α-particles and β-particles. We have seen that α-particles are helium nuclei and β-particles are electrons. The question arises, Where do these particles come from? The answer is that they come from the nuclei of the heavy, disintegrating atoms. It may astonish us that they are helium nuclei and not hydrogen nuclei that are shot out by the disrupting atoms. But we shall see later that the helium nucleus, consisting of 4 hydrogen nuclei and 2 electrons, is a very stable affair, so stable that it enters as a sort of indivisible unit into the structure of more com-

plicated nuclei. Now let us, remembering our general theory, trace exactly what happens in the above series of radium changes. A radium atom turns into an atom of radium emanation by losing an α-particle. The α-particle carries two units of positive charge. It is shot out from the nucleus of the radium atom, and therefore the new nucleus is minus two positive charges. That is to say, the nucleus of an atom of radium emanation carries two charges less than the nucleus of a radium atom. But the charge on the nucleus is, as we have seen, equal to the atomic number of the atom. It follows that the radium emanation atom must be placed two steps lower than the radium atom in the periodic table. But the α-particle contains four hydrogen nuclei. Therefore the atomic weight of the radium emanation atom must be four units less than that of the radium atom. The result of an atom losing an α-particle, therefore, is to give rise to a new atom whose atomic weight is less by four units, and which belongs to a place two steps back in the periodic table. What is the effect of losing a β-particle? The nucleus of every atom except

a hydrogen atom contains, besides a number of hydrogen nuclei, a smaller number of electrons. These electrons neutralise an equal number of the hydrogen nuclei contained in the nucleus of the atom, leaving over a number of hydrogen nuclei equal to the charge on the nucleus, which is itself equal to the atomic number of the atom. A β-particle shot out from the nucleus, therefore, leaves one extra hydrogen nucleus unneutralised. In consequence, the charge on the atom's nucleus increases by one unit, and therefore the atomic number increases by one. The new atom, therefore, moves one place up in the periodic table. And what happens to its atomic weight? Its atomic weight is unaffected, for we have seen that electrons play almost no part in contributing to the mass of an atom. The loss of an electron makes practically no difference to the weight of an atom. Besides, the new atom soon captures a free electron (of which there are always a large number about) to compensate for its extra positive charge. This electron does not fall into the nucleus, but joins the group of electrons which are rotating round the nucleus.

We are now in a position to understand the series of radium changes given above. Radium, with an atomic weight of 226, loses an α-particle and becomes radium emanation, with an atomic weight of 222. Radium emanation, losing an α-particle, becomes radium-*A* with an atomic weight of 218. The loss of α-particles continues, and radium-*A* gives rise to radium-*B*, with atomic weight 214. At radium-*B* the process alters. Radium-*B* loses a β-particle and turns into radium-*C*. The atomic weight is, of course, unaltered, so radium-*C* also has the atomic weight 214. Having got as far as radium-*C*, a very interesting thing happens. Some radium-*C* atoms, by shooting out an α-particle, pass straight to radium-C'', with an atomic weight of 210, and then, through radium-C'' losing a β-particle, to radium-*D*, also with an atomic weight of 210. Other radium-*C* atoms, however, shoot out a β-particle instead of an α-particle, and so become radium-C', with an unchanged atomic weight of 214. Radium-C' shoots out an α-particle and so it also becomes radium-*D*, atomic weight 210. Thus the two paths lead

to the same result, viz., radium-*D*. Radium-*D* is not stable, however; it loses a β-particle and becomes radium-*E*. That also loses a β-particle and becomes radium-*F*, *i. e.*, polonium, Both these substances, radium-*E* and polonium, have, of course, the same atomic weight, 210, as radium-*D*. Having reached polonium, the series has one more step to go. Polonium, by losing an α-particle, becomes lead, with an atomic weight of 206. With lead, the process of disruption seems to have stopped. There is no evidence that lead is disintegrating; if it is, it must be at an exceedingly slow rate which has hitherto avoided all means of detection. It must be noted here that the lead reached in this way has not the same atomic weight as ordinary lead. Ordinary lead has the atomic weight 207·2. By taking a different series of radioactive changes, starting from thorium, we also reach lead as the final substance. But the lead so obtained has an atomic weight of 208. These curious facts, and a number of others like them, we must now proceed to consider.

§ 4. *Isotopes*

The chemical and physical properties of an element depend on its atomic number, *i. e.*, on the positive charge carried by the nucleus of an atom of that element. And this positive charge is, as we have seen, a *resultant charge.* It is a result of the combination of a number of unit positive charges with a smaller number of unit negative charges. We can obviously reach the same resultant figure in as many ways as we please. If the resultant charge on the nucleus is to be 5, for instance, then we could take the combinations + 6 and − 1, or + 7 and − 2, or + 8 and − 3, and so on. Each of these arrangements would give atoms having identical chemical and physical properties. But their atomic weights would be different. The atomic weights depend, not on the resultant positive charge, but on the actual number of positive charges present in the nucleus, including those that are compensated for by negative charges as well as those that are not. In the above case, for instance, our atoms would have atomic weights 6, 7, 8, and

so on. And this is the only difference they would have. By no other chemical or physical properties could they be distinguished one from another.

It is therefore a very interesting fact, and one fitting in beautifully with our theory, that many elements have been shown to consist of a mixture of atoms having different atomic weights, but identical in every other respect. The element chlorine, for example, has the atomic weight 35·46. This number is about as far removed as it could be from being a whole number, and is therefore specially fatal to the theory that all atomic weights are simple multiples of the same unit. But it has been shown that chlorine is really a mixture of two groups of atoms, the atomic weight of the atoms of one group being 35 and the other 37. These groups are mixed together in about the proportion of 3 to 1, and the ordinary measured atomic weight of 35·46 is really the average weight of the mixture. Neon, again, whose atomic weight is ordinarily given as 20·2, is found to consist of two groups of atoms with atomic weights 20 and

22. Much more complicated groupings have been discovered. Thus krypton, whose atomic weight is put as 82·92, is made up of groups of atoms having the weights 78, 80, 82, 83, 84, 86. Such elements are called *Isotopes*, the name indicating that the groups of atoms belonging to these elements occupy the *same place* in the periodic table. It will be noticed that the atomic weights of these groups of atoms are all whole numbers. This is on the basis of oxygen taken as 16. On this basis hydrogen is not exactly unity, but is 1·008. It appears probable, then, that all atoms have atomic weights which are nearly, but not quite, whole multiples of hydrogen.

The existence of isotopes definitely destroys the great importance that chemists had always assigned to atomic weights. We have atoms of different atomic weights but of the same properties. Further, as we saw in studying the disintegration of radium into lead, we have elements of the same atomic weight but with wholly different chemical and physical properties. The atomic weight of an element, therefore, by no means suffices to determine its

chemical and physical properties. We see once more that the really important quantity to be known about an element is its *atomic number*, *i. e.*, its position in the periodic table. It is worth noting that the existence of isotopes was not suspected until comparatively recent times, although very delicate determinations of atomic weights have been practised for decades. The most refined measurements customary in such determinations never varied from sample to sample of the same element. Exactly the same mixture of atoms constitutes chlorine, for instance, wherever the chlorine is obtained, and always has done so ever since men began to study chlorine. The groups of atoms which make up chlorine or any other isotope must have been thoroughly and universally mixed long ages ago—in all probability before the formation of the earth's crust, when such universal and complete diffusion would have been possible.

§ 5. *Relativity and the Atom*

It is necessary, now, to say a little about the Restricted Principle of Relativity, since certain

points about the modern theory of atomic structure cannot be understood without it. But it is not necessary to explain the principle itself. It is only necessary to describe the relation between energy and mass that the theory shows to exist. In pre-Relativity mechanics, it was always assumed that the mass of a body was completely independent of its velocity. There was no reason to suppose otherwise. Whether a body was moving fast or slow, or whether it was at rest, its mass, when measured, was always found to be the same. But the theory of relativity asserts that the mass of a body does vary with its velocity. As the body moves faster its mass increases. The mass increases in such a way that, at the speed of light, it becomes infinite. This can only mean that the velocity of light is a natural limit, that no material body could possibly exceed this speed. If it be true that the mass of a body increases with its velocity, it might be thought that experiment would long ago have led us to suspect that fact. But the law according to which the increase occurs is such that the increase is not measurable except at

very great speeds. Now we are not familiar with bodies moving at very great speeds. We know of velocities such as 100 miles per hour and even, in astronomy, of velocities which reach a few miles per second. But velocities which are a considerable fraction of the velocity of light, viz., 186,000 miles per second, are practically unknown. It is the α- and the β-particles which furnish us with examples of bodies moving at speeds comparable with that of light. And experiments on these bodies show that their mass does increase with their velocity, and precisely in the way predicted by Einstein's theory. So that the ratio e/m, the ratio of charge to mass of an electron, varies with the velocity of the electron. As the velocity increases m increases and therefore e/m grows smaller. The value of e/m usually given, viz., $1 \cdot 77 \times 10^7$ (electromagnetic) units, is the value for low velocities, when m may be taken as the mass of the electron at rest. We will denote this value of m as m_0; m_0 is the mass of the stationary electron. At half the velocity of light, the mass of the electron is $1 \cdot 15\ m_0$, *i. e.*, it is about one-seventh greater.

If the electron is moving at nine-tenths the velocity of light its mass is $2 \cdot 3\ m_0$, or nearly two and a half times greater. At ninety-nine-hundredths of the velocity of light the mass of the electron is seven times its value at rest, and at the velocity of light itself, as we have said, its mass is infinite.

This result of relativity theory must obviously be borne in mind in any attempts to ascertain in detail what goes on inside an atom. If the mass of the rotating electrons is a quantity which enters into our calculations, then obviously we must remember that the mass varies with the velocity of rotation we ascribe to the electrons. Another important aspect of this theory is that it shows we must ascribe *mass* to *energy*. This, again, is a very novel conception. We are used to thinking of energy as something to which the property of possessing mass cannot be ascribed. The two things seem to have nothing to do with one another. But it can be shown that energy certainly does possess inertia, and the property of possessing inertia is what we really mean by mass. The mass of a body is, indeed, only

another way of measuring the total amount of energy it contains. Every piece of matter possesses a vast store of internal energy. If the piece of matter begins to move its energy is increased in virtue of its motion. Its mass also is increased. But the increase in mass due to increase in energy is usually extremely small. In any chemical combination which is attended by the development of heat, for instance, there is a certain loss of mass due to the energy radiated away during the process of combination. The resultant mass of the compound is less than the sum of the original masses of its constituents. But the loss which occurs in this way during any chemical process is exceedingly small, and the old law of the invariability of mass is, in all such cases, quite good enough. But there appears to be a beautiful and highly interesting exception. We have seen that there is reason to suppose that the helium nucleus, which is shot out of radioactive bodies as an α-particle, is a very stable structure. It is composed, as we have said, of four hydrogen nuclei and two electrons. The great stability of this structure suggests that its formation

was attended by a great expenditure of energy, so that an enormous amount of energy would have to be communicated to it to break it up. Now the atomic weight of helium is 4, and the atomic weight of hydrogen is not 1, but 1·008. Four times the mass of the hydrogen atom would give an atomic weight of 4·032. The suggestion is that the difference between this value and the actual measured value of 4, represents the *mass* of the *energy* lost in the process of combining the four hydrogen nuclei into the helium nucleus. This gives a measure, also, of the amount of energy that would be required to split up the helium nucleus into its original components. The amount of energy represented by this figure is really enormous. It is sixty-three million times greater than the energy expended in ordinary chemical processes, and this figure is a measure of how much more stable the helium nucleus is than an ordinary chemical compound. A chemical compound can often be dissociated merely by raising its temperature a few degrees, but even the enormous energy possessed by the fastest α-particles is only about a third of that required to dissociate the helium nucleus.

CHAPTER V: *Quantum Theory*

Chapter V

Quantum Theory

§ 1. *The Stability of the Atom*

WE have seen that the theory we have been describing, called the nuclear theory of the atom, gives a very satisfactory account of a large number of phenomena. The observed scattering of α-particles on passing through thin sheets of metal, the existence of isotopes, the changes which occur in radio-active phenomena, all receive very convincing explanations. There can be no doubt that the nuclear theory of the atom is essentially true, that the atomic models we have imagined correspond closely to actual atoms. But there is a fatal objection to this theory of the atom, as we have presented it hitherto. Such an atom could not continue to exist!

According to the classical theory of electro-dynamics every change of motion on the part of an electrically charged body is attended with

a radiation of energy. In wireless telegraphy, for instance, it is the rapid oscillations of the electrons in the sending apparatus which produce the electromagnetic waves. Each time an electron suffers a change in the direction or speed of its motion, or in both, it sends out an electromagnetic wave. Such a process cannot be kept up without a continual supply of energy. In the atomic model, as we have presented it, the outer electrons, which we imagine to be continually circulating round the nucleus, would be continually sending out energy. For a circular motion is a perpetually changing motion, and every change of motion on the part of a charged body is accompanied by the emission of energy. For an electron not to radiate energy, according to the classical theory, it must either be at rest, or be moving uniformly in a straight line. It is obvious that the outer electrons of our atom cannot be imagined as at rest. They would be attracted by the nucleus and simply fall into it, just as the planets would fall into the sun if they were robbed of their orbital motion. In order to counterbalance the attraction of the nucleus

the outer electrons must have a circular or elliptical or some such motion. And any such motion would be attended by a radiation of energy. As a result of this radiation of energy it can be shown that the orbit of the rotating electron would grow smaller and its velocity of rotation greater. This process would continue until finally the electron fell into the nucleus. That is to say, the atom, as we have depicted it, is, on the classical theory of electrodynamics, essentially unstable. The whole material world, as we know it, ought to have vanished long ago. Further, the spectrum of any element contains perfectly sharp lines which are situated in perfectly definite parts of the spectrum. The radiations from the atoms of a given element are perfectly definite; they do not assume all values. But if the outer electrons, from which these radiations proceed, are continually changing their orbital distances and velocities, then there ought to be a continuous succession of lines in the spectrum of that element, instead of the perfectly distinct and permanent arrangement which exists in fact.

So we see that, when we come to investigate the mathematical theory of our atomic model it turns out to be highly unsatisfactory. Are we, therefore, to abandon our model completely? Before we answer this question we will look at one or two other phenomena where similar extraordinary difficulties have been found. We will consider, in the first place, the phenomena of heat radiation, since it is here that the insufficiency of the old theory of electromagnetic radiation was first demonstrated. Let us consider the heat rays radiated by what is called a "black body." A black body is defined as one which absorbs the whole of the radiant energy that it receives. There is no substance which exactly satisfies this condition, but it is possible to produce the equivalent of it by artificial means. It was shown by the German physicist Kirchhoff that a space enclosed by an opaque envelope, and maintained at a uniform temperature, is filled with a radiation identical with that which would be emitted by a black body at the same temperature. If, therefore, a small hole be made in the opaque envelope, the rays which

escape through it will be the same as those that would be produced by a black body. Several physicists have studied these rays, and they have reached extraordinarily interesting results. The way in which the total amount of energy radiated is distributed amongst the different rays has been the chief object of their researches. The rays which come from the enclosure are of very different wave-lengths; they vary between wide limits. Corresponding to each wave-length is a certain fraction of the total energy radiated, and this fraction depends upon the length of the actual wave concerned in a rather complicated way. It is found, as the result of actual measurements, that the longest waves have very little energy. As the wave-lengths decrease the energy increases until a certain wave-length is reached where the energy has a maximum value. As we go on past this point to shorter and shorter wave-lengths the energy decreases, until for very short wave-lengths it is practically zero. Now this result is in the most flagrant contradiction with the theoretical calculations. According to the mathematical theory, the energy contained

in the very short wave-lengths should be very great. As the wave-lengths get shorter and shorter, tending towards zero, the energy contained in them should, according to the calculations, tend towards infinity. Observation shows that it tends towards zero. The contradiction is as striking as it could be.

We can see how extraordinary this observed result is if we consider an analogous case. Suppose that we have a number of corks floating on the surface of a bowl of water. Now suppose that, by some means, we agitate these corks, causing them to oscillate up and down in the water, and then leave them to themselves. We know that the oscillations will, after a time, die down. The whole mass, water and corks, will once again become quiescent. The difference is that the water will be slightly warmer. The energy which was contained in the oscillating corks is ultimately transferred to the molecules of the water and appears as heat energy. Now this result is quite in accord with the calculations. But if the result were to be analogous to the radiation result mentioned above, the corks would have to go on

oscillating for ever with undiminished vigour. We should all agree that such a phenomenon was highly mysterious. The results obtained in the radiation experiments are no less mysterious.

Let us turn to yet another phenomenon which is entirely contradictory of our expectations. It is found that light of high frequency, *i. e.*, of short wave-length, when allowed to fall on a metal, liberates electrons from the metal. The old scientific question of "How much?" immediately, of course, comes to the fore. We want to know the number of the electrons liberated and their velocities. And we want to know how these two quantities depend on the light which is used. We find, as the result of careful experiment, that the *number* of electrons liberated depends on the *intensity* of the light, but that the *velocity* of the electrons depends on the *frequency* of the light. This result is very surprising. We should have expected that the more intense the beam of light the higher the velocity of the liberated electrons. But only the number of electrons is influenced by the intensity. A

very weak beam of high frequency light will cause electrons to be shot out of the metal with high velocity. We get a firmer grasp of the paradoxical nature of this result if we first create X-rays by bombarding an anti-cathode with electrons, and then use the X-rays to liberate electrons from a metal. X-rays, as we have said, may be regarded as extremely high frequency light-waves. Now let us suppose that we produce some electrons in a cathode tube, and cause them to bombard the anti-cathode, so producing X-rays. The electrons will have a certain velocity, depending upon the voltage applied to the tube, and they will generate X-rays having a certain frequency. The higher the velocity of the electrons the higher the frequency of the resulting X-rays. These X-rays are now allowed to fall on a sheet of metal. Immediately electrons are liberated from the metal, and the astonishing discovery is made that the electrons so produced have the same velocity as the electrons which generated the X-rays. We may illustrate this result by an analogy used by Sir William Bragg. Imagine that we drop a plank, from the height of a

hundred feet, into the ocean. The impact produces waves in the ocean which spread out in circles around the point of impact. As the waves spread out they naturally get feebler and feebler, since the same total amount of energy is distributed over a longer and longer circumference. After travelling, say, two miles, let us suppose that the outermost wave reaches a ship. We are to imagine that, immediately the wave reaches the ship, it causes a plank to be shot up out of the ship to a height of one hundred feet. This case seems precisely analogous to the liberation of electrons by X-rays. The X-rays have spread out in ever increasing spheres from the point of impact, and yet, wherever they touch a metal, they liberate electrons having precisely the energy of the electrons which generated the X-rays.

The key to these extraordinary results is to be found in Planck's Quantum Theory. It was at the end of the year 1900 that Max Planck published his theory that energy is not emitted in a continuous fashion, but only in little finite packets, as it were. An oscillating atom, for instance, is to be conceived as sending out little

doses of energy, one after the other. It does not emit energy continually. And Planck asserted that the size of these little packets depended on the frequency of the oscillation, being greater the greater the frequency. Such an hypothesis is very strange, and is in entire contradiction to the classical dynamical theory on which the whole science of physics had been built. Yet, strange as the theory was, the results it was invented to explain certainly existed, and it could be shown that the old dynamics not only had not explained them, but could not possibly explain them. It was clear that any satisfactory explanation would have to be something quite revolutionary in character. And Planck's theory did, as a matter of fact, explain the observed radiation phenomena extremely well. Planck calculated, on his theory, how the energy of radiation should be distributed amongst the different wave-lengths, and his calculations precisely agreed with the experimental results. It is possible that, even so, this revolutionary theory would not have obtained general acceptance. But Einstein applied the theory to the phenomena attending

the liberation of electrons from metals under the influence of light, and his calculations, also, were shown to be in precise agreement with the evidence. The quantum theory, then, although strange and, in many respects, little understood, has become one of the great arms of modern physical research. It is still attended with very grave difficulties. The phenomena of electron emission from metals, for instance, certainly suggests that light energy exists in small bundles, dotted about round the surface of the sphere which was regarded as forming the old "wave-front." Each bundle, we may suppose, contains sufficient energy to liberate an electron with the velocity of the electron which gave rise to the bundle. On the other hand, certain well-known phenomena in light, particularly the phenomenon of "interference," seem utterly irreconcilable with this assumption; they are perfectly well explained on the old wave theory of light, but they seem quite inexplicable on the new quantum theory of light. It depends on which phenomenon we want to explain which theory we employ. Neither of them seem in the least adequate to

explain all the known phenomena, and they also seem quite irreconcilable with one another. The physicist must keep both and yet they cannot live together. A compromise has been tried. Sommerfeld and Debye, for instance, have endeavoured to work out a theory whereby the energy brought by the light waves has been regarded as continuous, but as being able, in some way, to accumulate until the amount contained in a quantum "bundle" is reached. Having accumulated to this amount, the energy is then supposed to work suddenly and to shoot out the electron with the requisite velocity. But the period required for this accumulation can be calculated, and it is found that, to explain the effects produced by X-rays, an accumulation period amounting to some years is required. So that the emission of electrons under the influence of X-rays should not take place until some years had elapsed. It is found, however, that the emission takes place immediately the X-rays are applied, and ceases instantly when they are discontinued. The contradiction is complete.

But the quantum theory, however puzzling

it may be in certain aspects, has shown itself competent to deal with very baffling phenomena. It was natural, therefore, faced by the great puzzle presented by the stability of the atom, to surmise that here, also, the quantum theory would prove competent to overcome the difficulties. In its original form, the theory could not be applied to the atom. It was first necessary to extend it. This was first done, and the theory successfully applied, by a brilliant young Danish physicist, Niels Bohr.

§ 2. *Bohr's Atom*

Before we go on to describe Bohr's conception of the atom we must make a few remarks about spectra, since the explanation of spectrum lines is one of the most important duties that an atomic model has to fulfil. The whole science of spectrum analysis began with Fraunhofer's discovery that light from the sun, if spread out in a coloured band by a prism, contained, besides its different colours, a large number of fine dark lines crossing the band at right angles to its length. Kirchhoff found that the

light from incandescent gases, when treated in the same way, also gave lines, although in this case the lines were bright lines. But he further found that a gas will absorb the same lines that it emits, so that if light be passed through a gas, dark lines will occur at the same positions as the bright lines occur when the gas is incandescent. Each chemical element was found to have its own appropriate series of lines, and these lines serve, with remarkable delicacy and exactitude, as a means of recognising the presence of these elements. The lines in the sun's spectrum, for instance, can be disentangled into the groups belonging to each separate chemical element in the sun. A similar analysis, performed on the light from various stars, enables us to say what chemical elements are present in those stars.

Every incandescent substance sends out light of several different wave-lengths. These different rays are, in the ordinary way, jumbled together, but, on being passed through a prism, they are separated out in an orderly manner. The spectrum ranges from the red to the violet. The waves giving red light are the longest

waves and those giving violet the shortest. Waves longer than red waves, the so-called infra-red waves, do not affect the retina of our eye as light at all, and the same remark applies to the waves shorter than violet waves, the so-called ultra-violet waves. But such waves, although they do not affect our eyes, can be made to affect certain chemical preparations; with ultra-violet waves, for instance, photographs may be taken of invisible objects, a fact perfectly well known to certain "spirit" photographers. Now each line on a spectrum corresponds to a definite wave-length. Light which is all of one wave-length is called monochromatic light; each line on a spectrum corresponds to a certain wave-length of monochromatic light. Corresponding to each line in the spectrum of a given element the wave-length can be measured, and the interesting question arises as to whether there is any relation between the lengths of the different waves emitted by that element. We shall see that there are such relations, and that Bohr's theory of the atom takes us some way towards explaining them.

In the first place, we have to assume, in applying quantum theory to the atom, that an electron describes a circle or an ellipse round the nucleus without radiating any energy. This assumption is in flat disagreement with the classical theory of electrodynamics, but it is in agreement with the quantum theory. Another assumption we must make, and which is not in agreement with the old theory, is that the electron can only move in certain orbits. If the orbit be a circular one, for instance, then an electron can only circulate round the nucleus at certain definite distances from it. It could not describe a circle whose radius was intermediate between two of these distances. Whatever one of the possible circles the electron is on, it will continue to traverse that circle indefinitely unless some external force acts on it. If an external force does act on it, then the electron passes directly to another of the possible circles. During this transition from one possible circle to another the electron radiates energy, and this energy is monochromatic, that is, it is energy of a perfectly definite wavelength. And the amount of energy so emitted

is a quantum of energy. The quantum of energy belonging to a certain frequency depends upon that frequency. Its amount is, in fact, equal to the frequency multiplied by a certain extremely small figure called Planck's constant. Thus the quantum, or the atom of energy, is not an invariable thing. Like the atoms of matter, energy atoms are of different sizes. The higher the frequency the greater the atom of energy. As we have said, a monochromatic radiation is emitted by the electron in passing from one possible orbit to another. This radiation has, of course, a definite wave-length and therefore a definite frequency corresponding to it. This frequency, multiplied by the quantity called Planck's constant, is equal to the total energy emitted by the electron in passing from one orbit to the other.

We have said that certain relations have been found to exist between the lines in the spectrum of a given element. It was in 1885 that Balmer discovered that the lines in the spectrum of hydrogen could be represented by a certain very simple formula. The frequen-

cies corresponding to a certain prominent group of lines in the hydrogen spectrum may be represented by multiplying a certain constant figure by the quantity ($\frac{1}{4} - \frac{1}{n^2}$) where n takes on the values 3, 4, 5, 6, 7. These are the five strongest hydrogen lines, and for them the quantity in the brackets becomes ($\frac{1}{4} - \frac{1}{9}$), ($\frac{1}{4} - \frac{1}{16}$), ($\frac{1}{4} - \frac{1}{25}$), ($\frac{1}{4} - \frac{1}{36}$), ($\frac{1}{4} - \frac{1}{49}$). Each of these values is to be multiplied by a certain figure, the same in each case, and the results will be the frequencies corresponding to each of these five lines respectively. Another series of lines in the hydrogen spectrum is obtained by using, instead of the general quantity in brackets given above, the quantity $\frac{1}{9} - \frac{1}{n^2}$, where n takes on the values 4, 5, 6, etc. Still another series can be obtained from the general formula $\frac{1}{1} - \frac{1}{n^2}$, where n has the values 2, 3, 4, etc. It is easy to see that the most general formula, including all these cases, is $\frac{1}{m^2} - \frac{1}{n^2}$. In the first formula we gave, for instance, $m = 2$. In the second $m = 3$, and in the third $m = 1$. Formulæ which are a trifle more complicated were discovered later, and were found to represent still other series of

lines. And these formulæ were applied to other elements besides hydrogen.

On Bohr's theory, when an electron passes from one orbit to another, it emits a certain quantity of energy, and the energy so radiated has a certain frequency. If, therefore, we subtract the energy possessed by the electron in its second orbit from the energy it possessed in its first orbit, we have the total quantity of energy emitted by it in passing from one to the other. The frequency, therefore, could be calculated from the subtraction of these two quantities. Now it is suggestive that Balmer's formula for the frequency, given above, is expressed by the subtraction of two quantities. Bohr showed that this was no accident, and that the two quantities in Balmer's formula do indeed correspond to the energies before and after the transition of the electron from one orbit to the other. In fact, Bohr was able, on his theory, to deduce Balmer's formula. It no longer appeared as a mere empirical rule, but as a theoretical consequence of the structure of the atom. This result was a most striking success for Bohr's theory to achieve. He also de-

duced, from his theory, the value of the constant figure which is used to multiply the different quantities in brackets given above; his calculated figure and the empirically ascertained figure were in precise agreement. The values of the different possible radii on which the electron in a hydrogen atom can move were also deduced by Bohr. The electron is most stable when on its first orbit, the orbit nearest the nucleus. This is the normal condition for a hydrogen atom. The actual diameter of a hydrogen atom in this condition can be calculated on Bohr's theory, and the value so obtained is found to be in agreement with the value obtained by quite other methods.

The fact that the spectrum of hydrogen possesses a number of lines, therefore, shows us that, in the immense number of atoms present in any specimen of hydrogen, there are always many whose electrons are passing from one orbit to another. In one atom an electron will be passing from the second to the first orbit, or from the third to the second, or from the fourth to the third, and so on. Such transitions must always be going on, for it is only in virtue of

them that the hydrogen atoms radiate any energy at all. The state to which all these changes tend is the most stable state, when the electron is on its first orbit. We may say, then, as Bohr puts it, that the spectrum of hydrogen shows us the formation of the hydrogen atom, since the transition to the successively decreasing orbits may be regarded as stages in the process by which the hydrogen atom reaches its normal condition.

§ 3. *The Fine Structure of Hydrogen Lines*

We may summarise the theory of the hydrogen atom we have given hitherto by saying that the hydrogen atom consists of a positive nucleus carrying one unit of charge, and that a single electron is describing an elliptical orbit about it. We can imagine a number of ellipses, of different sizes, enclosing the nucleus. Each of these ellipses will have a common focus, and it is at this focus that the nucleus is situated. The single electron can move on any one of these ellipses, but only on these; it cannot describe an intermediate orbit. Under the influ-

ence of an external force the electron may jump from one of these ellipses to another. During this jump it radiates energy in the form of monochromatic waves. As long as it remains on any one of these ellipses it is not radiating energy. These elliptical motions are called *stationary states.* The electron only radiates energy, then, in passing from one stationary state to another. This simple theory suffices to explain the positions of the lines in the hydrogen spectrum. We reach a formula which is exactly like Balmer's formula showing the distribution of these lines.

When we come to look more closely into the matter, however, we find that there is a factor we have neglected in our calculations. We have said that the electron describes an ellipse about the nucleus. We suppose that it describes this ellipse in obedience to the ordinary laws which regulate the motion of a single planet about the sun. It is a peculiarity of such motion that the speed is not uniform. A planet, in its elliptical orbit about the sun, is sometimes moving faster and sometimes slower, depending upon which part of the ellipse it is

describing. At those parts of the ellipse which are nearest the sun the planet is moving fastest. At the parts most remote from the sun it is moving most slowly. As precisely the same laws apply to our electron moving round the nucleus, we have to take into account the fact that the speed of the electron in its orbit is continually changing. This is where the theory of relativity comes in. We have seen that it is a consequence of that theory that the mass of an electron varies with its velocity, becoming greater the greater the velocity. Our electron, therefore, is not only moving with a varying speed; it is also moving with a varying mass. What influence will this variation of mass have on the motion?

This problem was solved by Sommerfeld. The result is that the electron continues to move in an almost elliptical orbit, but this orbit itself is slowly and uniformly rotating. The actual motion of the electron in space is a combination of these two motions. The effect of this on the spectrum of hydrogen will be that corresponding to each hydrogen line there will be two or three lines extremely close together.

Each hydrogen line will really consist of more than one line. These lines will be so close together that it would be almost impossible to see them separately. Nevertheless, measurements have been made, and these measurements are in agreement with Sommerfeld's theory. The fine structure, as it is called, of the hydrogen lines, is due to the variations in mass of the electron in describing its orbit about the hydrogen nucleus. The complete explanation of the hydrogen spectrum requires both quantum theory and relativity theory; conversely, the striking agreement between calculation and observation in the hydrogen spectrum greatly supports both these theories.

So far we have considered the theory, in detail, only in its application to the hydrogen atom. The hydrogen atom is the simplest atom, and we should expect the theory to be most adequate in dealing with this case. But although the sheer complexity of the heavier atoms has hitherto prevented so complete a description of them being formulated, the general theory of their structure, as we shall proceed to show, has much that is of interest and value to tell us.

Chapter VI: *The Grouping of Atoms*

Chapter VI

The Grouping of Atoms

§ 1. *The Outer Electrons*

ANY theory of the atom which is to secure our assent must, in broad lines if not in detail, account for the remarkable periodicity in the properties of the chemical elements. We have already shown that this periodicity, the recurrence of similar physical and chemical properties, led Mendeléev to construct the Periodic Table. In each of the columns of the diagram in Chapter IV the elements run through a cycle of chemical properties which is approximately repeated in the next column. This repetition of properties is not perfectly regular. The columns are of unequal length; some contain 8, some 18, and some 32 elements. But the periodicity, although not perfectly simple, is quite unmistakable, and is one of the most important and outstanding properties of the chemical elements. Instead of arranging the

atoms by their general chemical properties we may arrange them according to some specific property. We may, for instance, arrange them in accordance with what is called their "atomic volumes." If we do this we again get a periodic relation. Still other properties, such as "compressibility," "expansion coefficient," etc., show the same intriguing peculiarity. All these properties seem to be connected with the actual amount of space taken up by the atom. They are not properties of the nucleus; they are dependent upon the outer electrons. And also, if we study the visible spectra of the various elements, we find the same curious recurrence. All those elements which are called Alkalis, for example, have spectra which seem to be constructed on the same ground plan. The different alkalis differ enormously from one another in the complication of their structure; their atomic numbers are 3, 11, 19, 37, 55, so that we pass from a system containing three circulating electrons to one containing fifty-five. And yet their spectra are fundamentally the same. Here, also, we are concerned with the outermost electrons. The nuclei of these atoms

are not concerned in their visible spectra. The nuclei of the various atoms, arranged according to their atomic numbers, simply show a straightforward advance from complexity to complexity. There is no kind of repetition or recurrence in the properties which depend on the nucleus. But the way in which the outer electrons are arranged does show a recurrence, and all those physical and chemical properties which show a recurrence may be assumed to depend on the outer electrons. Thus we may say that *the chemical properties of an atom depend not on its nucleus, but on its outer electrons.*

The visible spectrum, as we have said, depends upon the arrangement of the outer electrons. But *X*-rays also possess a spectrum. The *X*-rays emitted from any source are not all of the same wave-length and these waves, by a method of which we shall learn more later, can be arranged in order like those of visible light. Now the *X*-ray spectra of the elements do not manifest a recurrence. They advance, in a straightforward way, with the atomic number. They depend upon the inner part of the atom

and not upon the outer electrons. And it is because they originate in the neighbourhood of the nucleus, where the atomic forces are most intense, that the X-rays possess their great penetrative power. Periodicity is not an inner, but only an outer, property of the atom.

The great dominating factor which governs the properties of an atom is the charge on its nucleus. We see this very clearly in the case of isotopes. Two isotopic varieties of an element cannot be distinguished from one another by their chemical properties. The outer electrons are arranged in the same way in the two varieties of atoms, and it is this arrangement which determines the chemical properties. Their visible spectra are also the same, and so are the spectra in the ultra-violet region. This fact furnishes an even more exact proof that their outer electrons are arranged in the same way than does the identity of their chemical properties. Two isotopic elements also have the same X-ray spectrum; therefore the inner structure of the atoms, also, is the same in the two cases. The whole structure of the atom is evidently dependent on the charge carried by

the nucleus; where this charge is the same the atomic structure is the same.

The general question of how the electrons in a heavy atom are to be supposed to be arranged is one of great difficulty, and no perfectly precise answer can yet be given. There are certain general considerations, however, which enable us to give a partial answer to the question. In the periodic table each column ends with what is called an "inert gas." These elements are so called because they possess great stability; they are not in the least eager to enter into combination with other elements. Let us consider the element argon, for instance. It is an inert gas, and occurs at the end of the second group of eight in the periodic table. Its atomic number is 18. It therefore contains 18 electrons rotating round the nucleus. Owing to the marked stability of argon we must suppose that these 18 electrons are arranged in some peculiarly stable configuration. The natural ideal of every atom would be to reach so stable a condition. It is a state to which every atom aspires. The atom of chlorine, which just precedes argon in the table, and therefore pos-

sesses only 17 electrons, shows a marked disposition to capture one additional electron. It is striving towards the perfect state of possessing 18 electrons—not because it requires the extra electron to become electrically neutral, of course, but because the extra electron gives it greater mechanical stability. On the other hand, the element potassium, which immediately follows argon in the table, shows a marked tendency to get rid of one of its 19 electrons—again in order to attain the perfect state of possessing 18 electrons. If we go back to sulphur, which has 16 electrons, or forward to calcium, which has 20 electrons, the same tendency manifests itself. Sulphur has a tendency to capture two electrons and calcium has a tendency to lose two electrons. We can understand, therefore, why the Germans call the inert gases, like argon, the "noble" gases. It is not only that they are sublimely inactive, but their condition is that to which all the others aspire.

The great stability of the inert gases, and the fact that they occur at the end of each period in the periodic table, so that, immedi-

ately after each inert gas, the whole cycle of chemical properties begins again, show us that they are, as it were, the natural terminations of the building schemes which led up to them. After each inert gas a fresh building scheme has to be adopted for the next group of atoms. We have seen that each step along the periodic table means the addition of a fresh electron. We can imagine the outer electrons of an atom to be arranged in a ring, or on the surface of a sphere, or in what configuration we like. When a fresh electron has to be added to produce the atom one step on in the periodic table, we may imagine that, in general, this new electron joins the rest. It takes its place in the ring or on the sphere or whatever it may be. But there will come a moment when the addition of a fresh electron will spoil the stability of the whole structure. There will be no place for it in the ring, and it will have to start a new ring, by itself, outside the existing one. When yet another electron joins up, it will help the first one in establishing the new ring. Presently the new ring will itself have all the members it can stably hold, and further electrons

will have to build up yet another ring. The process will not be quite so simple as this, for as outer rings continue to be built they will so influence the inner rings that these will be able to take more members than they could originally accommodate. But, in the broadest outlines, the process is as we have described. Now the inert gases form such points of departure. By the time an inert gas is reached the system which led up to it has done all it could; it has fulfilled itself in producing an inert gas. If atom building is to continue, it must be on a different system, although the system of the new atom will, of course, resemble the system of the atom to which it is connected by a line in the periodic table. In just the same way, all the different inert gases have systems which resemble one another.

The inert gas which precedes argon is neon, an element possessing ten electrons. There is reason to suppose that it contains 2 inner and 8 outer electrons. The inert gas preceding neon is helium, the first of the inert gases, and helium has 2 electrons. With the obvious exception of helium it is supposed that the chemi-

cal similarity of all the inert gases is due to their possessing 8 outer electrons, however many groups of inner electrons they may have. The following table, showing the number and arrangement of the electrons in successive groups, going outwards from the nucleus, has been proposed by Bohr.

Helium	2
Neon	2, 8
Argon	2, 8, 8
Krypton	2, 8, 18, 8
Xenon	2, 8, 18, 18, 8
Radium Emanation	2, 8, 18, 32, 18, 8

How are we to consider these different groups of electrons to be arranged? No precise answer can yet be given to this question, but the whole trend of the most modern speculations is to emphasise the fact that it is not sufficient to regard the different groups as lying in plane rings. It is necessary to investigate the *spatial* configuration of the electronic orbits. It is very probable that different electrons move in orbits which are inclined at various angles to one another. Even in the solar system, the planets do not all rotate in precisely the same

plane. In the electronic orbits, we must imagine these differences to be much greater. It has even been suggested that the number 8, which occurs with such frequency in electronic groups, may indicate that these groups of eight are arranged like a cube, one electron being at each corner. The idea has something to recommend it, although it appears that such an arrangement cannot be explained by the known forces within the atom. But it serves as an indication of the direction in which a solution is being sought. We shall now deal with this question in more detail.

§ 2. *Hydrogen and Helium*

Hydrogen and helium are the two members of the first group in the periodic table, and we shall now proceed to examine their atomic structure. We have already described the structure of the hydrogen atom in some detail. We know that it consists of a single electron rotating about a nucleus. The electron can circulate on a number of different orbits, but its most stable state is obtained when it circu-

lates on the first orbit, the one nearest the nucleus.

When we come to the helium atom the question is much more complicated. A helium atom which had but one electron would be essentially similar to a hydrogen atom, with the difference that the nucleus would carry two positive charges instead of one. The real problem of the helium atom is to determine the way in which the second electron enters into its constitution. A spectrum of helium consists of two complete series of lines, and for this reason helium was supposed to consist of two different gases, called "orthohelium" and "parhelium." But it is now known that these two series of lines arise from the fact that the second electron can enter into the constitution of the helium atom in two different ways. The two electrons may be describing orbits of the same kind, but inclined at an angle to one another, or they may be describing orbits of different kinds, one outside the other. The first case gives the most stable state for the atom, and in reaching it the atom emits the spectrum which used to be referred to "parhelium."

The second case is less stable and the process of reaching it gives the "orthohelium" spectrum. This state was produced experimentally by bombarding helium atoms with electrons. Such a bombardment could produce what was called a "metastable" condition of the helium atom, and it was found that the atom could not return to its normal condition merely by radiating energy. The bombardment had caused the second electron to move in an orbit outside that of the first electron—an orbit of a different kind. And, having once done this, the second electron could not make a jump back to its original orbit. Before it could return to normal the "metastable" atom had to interact with atoms of other elements—it had to go through a sort of chemical reaction. In its normal state, then, the helium atom may be said to consist of two electrons moving round the nucleus in similar circles, these two circles being inclined at an angle of 120° to one another. And owing to the interaction between the two electrons the planes of these two circles are slowly moving. So that already, and when we are dealing with an atom

containing only two electrons, we are in the presence of very considerable complications. The detailed working out of the constitution of more complicated atoms would obviously be a task of immense difficulty. Bohr has been able, however, to say something about the broad lines of their structure.

§ 3. *Lithium—Neon*

We now come to the second group of the periodic table, a group possessing eight members. We begin with lithium. Its atomic number is 3, and therefore an atom of lithium consists of 3 electrons revolving about a nucleus. We shall assume that two of these electrons move in orbits similar to those characteristic of the normal helium atom, that is, in orbits which are not in the same plane but which are otherwise similar. This assumption is very natural, for the normal structure of a helium atom is a very stable condition. It is distinctly more stable, for instance, than the structure of the hydrogen atom. Helium is the first of the inert gases. We assume, then, that

two of the electrons in a lithium atom move as do the two electrons of the helium atom. How are we to suppose the third electron to move? The spectrum of lithium shows us that the third electron moves in orbits which are altogether outside the region containing the first two electrons. The spectrum also shows that the third electron sometimes moves in orbits which, although they lie outside the region of the first two electrons for the greater part of their length, yet, at their nearest point to the nucleus, approach it as closely as do the first two electrons. These are the orbits characteristic of the lithium atom in its normal state. The firmness with which the outer electron is held in these orbits is only about one-third of that with which the electron in a hydrogen atom is held, and only about one-fifth of that with which the helium electrons are held. The chemical properties of these three elements, therefore, depending, as they do, on the outer electrons, should be very different, as, in fact, they are.

We may assume that, in any atom, the third electron moves in the same kind of orbit as does

the third electron of the lithium atom. This orbit is, as we have said, very excentric. It may be regarded as markedly elliptical. That part of it nearest the nucleus is within the region in which the two inner electrons move. The rest of it extends far beyond this region. We may imagine that the fourth, fifth, and sixth electrons move in similar orbits. There is reason to suppose that the four electrons, from the third to the sixth inclusive, which move in these excentric orbits, are so distributed as to form an exceptionally symmetrical configuration. Each of these outer electrons penetrates to the region occupied by the inner electrons, but not at the same moment. Bohr supposes that the outer electrons reach their nearest point to the nucleus separately at equal intervals of time.

This structure carries us as far as carbon, which has six electrons. Lithium has one outer electron, beryllium two, boron three and carbon four. Each of these outer electrons moves in very excentric orbits which enclose and partly penetrate the approximately circular orbits within which the two inner elec-

trons move. This method of building reaches completion in the carbon atom. If yet another electron were added to the four outer electrons of carbon the symmetry of the arrangement would be destroyed. There is, as it were, no room for five such orbits. Also, the fact that the elements in the second half of this group in the periodic table have very different properties from those in the first half suggests that a new system of building comes into existence directly we proceed beyond carbon. Bohr supposes that in nitrogen, an element possessing seven electrons, the seventh electron moves in a large and approximately circular orbit. It lies completely outside the two inner electrons, although the outermost parts of the excentric orbits on which the other four outer electrons lie extend beyond it. The eighth, ninth and tenth electrons also move in large circular orbits of this kind. The great stability of the last element reached in this way, the inactive gas neon, suggests that the final arrangement possesses great symmetry. We must suppose that, with this element, the four large circular orbits are not only sym-

metrical amongst themselves, but also in relation to the four elliptical orbits.

§ 4. *Sodium—Argon*

We have, so far, considered two types of orbits, the approximately circular, and the markedly elliptical. For the first two electrons we assume circular motion. For the next four we assume elliptical motion, and for the next four we again assume circular motion. In this way we have got as far as neon, and we now begin another group of the periodic table. Acting on the same general principles, we shall assume that the eleventh electron inaugurates a new era of elliptical orbits. These orbits are very elliptical. For the most part they are well outside the orbits of the first ten electrons, but for part of their course they, like the first group of elliptical orbits, penetrate even closer to the nucleus than do the two innermost electrons. The existence of such markedly elliptical orbits, passing, during part of their course, so close to the nucleus, greatly helps the stability of the atom. In the distri-

bution of the twelfth, thirteenth, and fourteenth electrons we meet conditions similar to those we encountered when considering the fourth, fifth, and sixth electrons. There seems to be an exception in the case of aluminium, the element whose atom contains 13 electrons. In this case the thirteenth electron seems to move in a less markedly elliptical orbit. But Bohr does not regard this behaviour as typical for the thirteenth electron in all atoms; it is peculiar to aluminium, where the thirteenth electron is also the last electron. By the time we get to silicon, containing 14 electrons, we find the thirteenth electron, like the eleventh, twelfth, and fourteenth, moving in the markedly elliptical type of orbit inaugurated by the eleventh electron. As in the preceding cases, we suppose this type of construction to be completed when we have four electrons describing these new orbits. The fifteenth electron introduces a new system, just as the seventh electron did. But whereas the seventh electron introduced an almost circular type of orbit, the fifteenth electron continues with the excentric type of orbit, although the excentricity is not

so marked as in the case of the orbits we have just left. These new orbits are excentric enough to penetrate closer to the nucleus than do the circular orbits inaugurated by the seventh electron, but they do not reach the region of the two innermost electrons. These orbits will accommodate four members, so that this type of construction will carry us up to the atom possessing 18 electrons, *i. e.*, up to the element argon. Thus we again reach an inert gas, and, allowing for the greater complexity, we see that its symmetrical properties closely correspond to those of the preceding inert gas, neon.

§ 5. *The Remaining Elements*

The development we have been describing hitherto is straightforward in the sense that fresh groups of electrons have been regarded as possessing fresh types of orbits which are, as it were, independent of those previously existing. We have not considered the later electrons as causing any development of the inner groups of electrons. That there must be some interaction is obvious, but we have not

found it necessary to assume that the interaction is sufficient to cause any fundamental modification of the orbits already established. When we come to the fourth period of the periodic table, however, matters are different. As we see from the diagram in Chapter IV, the fourth period contains 18 elements. At the beginning of this period the atom continues to develop in a way analogous to that we have already studied. The first two elements of this period are, as shown by the connecting lines, analogous to the first two elements of the third period. But then occurs a group of eight elements which do not correspond, in our diagram, to anything in the third period. And after this group occur two elements which are again analogous to the first two elements of the third period. Why is it that we have this interregnum, as it were, lasting over eight elements? Bohr's answer is that we are here concerned with the development of one of the inner groups of electrons. The normal system of atom building, as we have sketched it, cannot now proceed. The later electrons captured

will now be concerned in the internal re-arrangement, and only when this is completed will the normal process be able to proceed.

This theory gives an interesting explanation of the facts that many elements of the fourth period differ markedly from the elements of the preceding periods in their magnetic properties and also in the characteristic colours of their compounds. That highly magnetic substance, iron, for instance, occurs in the fourth period. To understand the explanation, offered by the theory, of the magnetic properties of these elements, we must revert to the familiar fact that an electric current is always attended by magnetic force. Electric currents are constituted by the movements of electrons, and the moving electrons within an atom will give rise to their appropriate magnetic forces. Now we may imagine that, in any thoroughly symmetrical arrangement of the electrons within an atom, these magnetic forces form a closed system within the atom, so that no resultant external effects are manifested. With any markedly unsymmetrical arrangement of the

electrons, however, we may expect appreciable external magnetic effects to manifest themselves. Bohr supposes, therefore, that the process of reorganisation within the atom which characterises a group of elements in the fourth period, is attended by the lack of symmetry which would result in magnetic forces being exhibited. Where the symmetry is at last restored the magnetic effects cease. In Bohr's words: "On the whole a consideration of the magnetic properties of the elements within the fourth period gives us a vivid impression of how a wound in the otherwise symmetrical inner structure is first developed and then healed as we pass from element to element."

The characteristic colours to which we have alluded also find an explanation on this theory. These colours are due, of course, to the absorption of light, and they are thus evidence that energy changes are going on comparable with those giving visible spectra. This is in contrast to the elements of the earlier periods, where the electrons are more firmly held and where the less rigid conditions, due to the de-

ELEMENT.	ATOMIC NUMBER.	NUMBER OF ELECTRONS IN DIFFERENT TYPES OF ORBITS.																						
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Helium	2	2																						
Neon	10	2	4	4																				
Argon	18	2	4	4	4	4	–																	
Krypton . . .	36	2	4	4	6	6	6	4	4	–	–													
Xenon	54	2	4	4	6	6	6	6	6	6	–	4	4	–	–	–								
Niton	86	2	4	4	6	6	6	8	8	8	8	6	6	6	–	–	4	4	–	–	–	–		
?	118	2	4	4	6	6	6	8	8	8	8	8	8	8	8	–	6	6		–	–	–	4	4

Table showing distribution of Electrons in the Inert Gases, including a hypothetical element of atomic number 118.

velopment of an internal group of orbits, do not occur.

The building up of the rest of the elements, up to and including the seventh period, may be supposed to take place on the broad lines we have now laid down. The process is a double one. New groups of outer orbits will be formed, and also there will be a development of groups of inner orbits. The whole process is very complex, and no attempt has yet been made to examine it in detail.

The seventh period ends abruptly with uranium, whose atomic number is 92. The last elements in this period are all radioactive, and, as we have said before, it seems probable that an element of higher atomic number than 92 would be too unstable to exist. Nevertheless, on the principles we have followed hitherto we can construct theoretically, and in its main lines, the structure of an atom having a higher atomic number than 92. The last inert gas known to us, niton, has an atomic number 86. The next inert gas, if it existed, would have an atomic number 118. Bohr gives a table, which we reproduce, showing in

some detail the number of electrons and the characters of their orbits for the six inert gases. He includes, as a seventh, the imaginary gas having an atomic number 118 and shows its hypothetical construction.

Chapter VII: *The Inner Regions*

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The Inner Regions

§ 1. *X-Ray Spectra*

IN speaking of X-rays we have referred to their wave-lengths and to their spectra, but we have not yet given any indication as to how these wave-lengths are measured. The most satisfactory method of determining the wave-lengths of ordinary light is by means of a "diffraction grating." This apparatus consists, essentially, of a sheet of glass on which a large number of very fine lines have been ruled very close together. The lines should be parallel and equidistant. Now the distance between two adjacent lines should be of the same order of magnitude as the wave-lengths to be measured. The lengths of visible light waves are comprised between 4×10^{-5} cm. and 7×10^{-5} cm., *i. e.*, they lie between 4 and 7 hundred-thousandths of a centimetre. X-rays, as we have said, have wave-lengths about 10,000

times smaller than this. It is difficult enough to rule lines close enough together for the distances to be comparable with the lengths of light-waves; it is utterly impossible to rule them ten thousand times closer still. The distance between adjacent lines would have to be of the order of 10^{-8} cm., *i. e.*, of the same order of magnitude as the molecular distances in a solid body. Manifestly such an apparatus is impossible to construct. But it so happens that nature has provided such an apparatus.

Certain mineralogists and mathematicians were long ago concerned to elucidate the regular shape and structure of crystals in terms of regular arrangements of their molecules or atoms. These molecules or atoms were supposed to be arranged in definite patterns, so that a crystal consisted of layers, arranged one behind the other, containing these regular assemblages. The distance between the molecules or atoms, so arranged, would be of the order of 10^{-8} cm. A crystal of salt, for instance, would have as the distance between its molecules $5{\cdot}6 \times 10^{-8}$ cm. The brilliant idea occurred to a German scientist named Laue

that such an arrangement really constituted a sort of diffraction grating and one, moreover, of just the right dimensions to serve for the measurement of *X*-ray wave-lengths. The realisation of this idea was highly successful, and the employment of crystals has not only served to measure *X*-ray spectra, but has also taught us a great deal about the structure of the crystals themselves. It is now possible, employing this method, to obtain photographs of *X*-ray spectra.

As a result of these researches we now know that the wave-lengths of *X*-rays vary within fairly wide limits, according to the conditions of their emission. The longest waves are about 12×10^{-8} cm. in length, while the shortest are about $\cdot 3 \times 10^{-8}$ cm. The shorter the wave the greater its penetrative power or "hardness." Now we have already said that each of the chemical elements, on being bombarded by cathode rays, emits a group of *X*-rays which is characteristic of it. The hardness of these *X*-rays varies with the substance that emits them, and in such a way that the greater the atomic number of the substance the harder are

the emitted rays. We are concerned here with a wholly atomic phenomenon, for if a substance be chosen as the anti-cathode which is a compound of two or more elements, it is found that the resultant X-ray emission, when the anti-cathode is bombarded, is really a combination of the X-ray groups which would be emitted separately by the elements that have gone to make up the compound. These important facts were discovered by Barkla, who also discovered that there were two series of X-rays in the characteristic X-ray emission from an element. He called these two series the K-group and the L-group. He observed that the lighter elements (up to silver) gave the K-group of X-rays, and that heavy metals (such as gold and platinum) gave the L-group. Of these two groups, the K-group is the more penetrating. The harder or more penetrating the X-rays, the greater the impact of the cathode rays necessary to produce them, and Barkla saw that the K-group, in the case of the heavy metals, would be so hard that the experimental methods known to him would not suffice to produce them. Similarly, the L-group

for the lighter elements would be too little penetrating, too soft, to be observable by the then known means. Barkla had determined the hardness of the rays he obtained by measuring their absorption by thin sheets of aluminium. And he had established a relation, as we have said, between hardness and atomic weight.

These results were made much more precise when the analysis of *X*-ray spectra by crystals replaced the absorption method of measurement, and when the wave-lengths so determined were related, not to the atomic weight, but to the atomic number. Besides the *K*- and *L*-groups, a third group, called the *M*-group, has been discovered. The *M*-group of rays is still softer than the *L*-group. The *K*-group, so far as our means of observation carry us, begins with sodium, whose atomic number is 11. With this light element the *K*-group, the hardest of the three groups, is distinctly weak. As the atomic number advances the *K*-groups emitted by the corresponding elements grow harder and harder, reaching their extreme degree of hardness with wolfram, whose atomic

number is 74. For one and the same element, emitting both the *K*-group and the *L*-group, the *L*-group is much the softer. The *L*-group has been observed with copper, whose atomic number is 29, and here it is even weaker than the *K*-group of sodium. From copper onwards the *L*-group gets harder and harder, and it has been observed right up to the last of the elements, uranium. The still weaker *M*-group has only been observed so far with the heaviest elements, and even then special precautions have to be taken to observe it at all. These three groups of rays together make up the *X*-ray spectrum.

§ 2. *The K-Group*

Moseley, probably the most gifted of the young English men of science killed in the war, was the first to make a considerable advance on Barkla's work. His first photographs (1913) were devoted to the *K*-group, and extended from calcium, with atomic number 20, to copper, with atomic number 29. These elements were used, successively, to form the anti-

cathode of a cathode tube, and were therefore bombarded directly by electrons. To obtain the *X*-ray spectra he used, of course, the method of crystal analysis, but not in its most modern form. He established the following results.

As the atomic number increases the corresponding lines in the spectrum move regularly in the direction of smaller wave-lengths, that is, the hardness of the lines increases with the atomic number. This result, in a less definite form, was, as we have seen, already reached by Barkla.

Each element gives two *K*-lines. The stronger, more obvious, line corresponds to the longer wave-length. This line in the *K*-spectrum of an element is called the $K\alpha$-line. The weaker line is the harder line, *i. e.*, it corresponds to the shorter wave-length. This line is called the $K\beta$-line.

The *X*-ray spectrum of an element is purely a property of the atoms of that element. Brass, for instance, which is an alloy of copper and zinc, gives four *K*-lines, of which two are the *K*-lines of copper, while the other pair

are the *K*-lines of zinc. Thus the *K*-spectrum of a complex substance is obtained by merely adding together the *K*-spectra of its elementary constituents.

The fourth result is of particular interest. It will be remembered that, for a few places in the periodic table, we inverted the order of the elements as given by their atomic weights. There are two or three places where a heavier element is put before a lighter one. The whole complex of the chemical and physical properties of such pairs of elements is allowed to determine their position in the periodic table, even when this is not in agreement with the atomic weight. Nickel and cobalt form such a pair. Cobalt is heavier than nickel, with an atomic weight of 58·97 as against an atomic weight of 58·68. Nevertheless, cobalt is written before nickel. This order, justified by general considerations, was completely confirmed by the *X*-ray spectra of these elements. The *K*-group for nickel has harder lines than the *K*-group for cobalt, and the increase in hardness corresponds to an advance of one step in the periodic table. Here we have a clear

proof that the *X*-ray spectra follow the order of the atomic numbers, not the order of the atomic weights. To settle this point was the original object of Moseley's research.

The fifth result which emerges from these researches is also of great interest. We have spoken of gaps in the periodic table and we have left spaces for elements which have not yet been discovered, but to which we have ascribed appropriate atomic numbers. In Moseley's original research there was a gap between calcium and titanium. This gap was immediately revealed by the *X*-ray spectra. The advance in hardness from one element to another is quite uniform, and in passing from calcium to titanium a sudden jump was found, corresponding to the omission of one element. This missing element is known. It is the rare substance named Scandium, with atomic number 21. Its absence from Moseley's series was at once revealed by the *X*-ray spectra. The regularity of the growth in hardness of the *X*-ray spectra enables us, without ambiguity, to say precisely how many elements (up to uranium) are yet undiscovered, and exactly

whereabouts they occur in the periodic table. Thus, corresponding to atomic number 43, there is a missing element. It has received the name Ekamanganese. Other gaps in the system occur at atomic numbers 61, 75, 85, and 87. The study of the X-ray spectra of the elements, therefore, enables us to say definitely that five elements are missing.

Moseley's results have been followed up, and his experiments repeated with better apparatus. The main discoveries that have been made by these later researches on the K-group are that there is a third line belonging to the group, and that the $K\alpha$-line really consists of two lines very close together—what is called a doublet. The third line of the K-group is even weaker and harder than the $K\beta$-line. It is called the $K\gamma$-line. The same law holds for this third line as for the other two. Like them, it increases in hardness for elements of increasing atomic number.

The beautiful simplicity and precision of the results make this research on the K-group one of the most interesting in all the modern work on the atom.

Of the *L*- and *M*-groups we need only say at present that they contain a large number of lines of which many are doublets. The general law of their variation in hardness with the atomic number is the same as for the *K*-group.

§ 3. *The Electrons near the Nucleus*

We shall now proceed to show how these experimental facts are explained by the theory of atomic structure that we have outlined. In doing so we shall present the problem in a rather simplified form, but one which serves, in its main lines, as the basis for the detailed examination which Bohr, and one or two others, are attempting. We recall again the fact that the atom is regarded as a kind of planetary system, of which the nucleus is the central body and the electrons the revolving planets. We have already discussed the way in which we may suppose these electrons to be arranged. They exist in groups; each member of any one group moves in the type of orbit characteristic of that group. We shall find that it simplifies our ideas and does not essentially disturb the

main lines of the theory if we imagine these groups of electrons to be situated on circles all centring about the nucleus. The circles get larger and larger, of course, as we proceed outwards from the nucleus. The circle closest to the nucleus we shall call the *K*-circle and the others, as we go outwards from the nucleus, the *L*-, *M*-, *N*-, etc., circles.

Let us now consider how we may suppose a radiation belonging to the *K*-group to be caused. We may suppose the first step to consist in the removal of an electron from the *K*-ring to the periphery of the atom, or else outside the atom altogether. If this removal be effected by a cathode-stream bombardment, we may imagine that it is the result of the direct impact of one of the bombarding electrons on the electron of the *K*-ring. A certain minimum amount of energy is necessary for this impact to be powerful enough to remove the electron. The electrons of the *K*-ring, the innermost ring, are powerfully attracted by the nucleus, and the bombarding electron must be moving sufficiently fast for its impact to overcome this attraction. There is therefore a certain mini-

mum velocity below which the cathode-stream bombardment cannot detach an electron from the *K*-ring. The higher the atomic number the greater the charge on the nucleus, and the more firmly, therefore, the electrons in the *K*-ring are held. For elements of high atomic numbers, therefore, only the most intense bombardment would suffice to detach an electron from the *K*-ring.

When the electron is detached, the *K*-ring is left incomplete, and an electron from another ring will rush to take the vacant place. Now we must remember that each ring corresponds to a different level of energy, in accordance with Bohr's quantum theory of the atom. In passing from one ring to another an electron passes from one energy level to another. A certain amount of energy is liberated by the process, and this energy manifests itself as a radiation. It will be what we have called a "monochromatic" radiation, that is, it will be of one definite wave-length. It will furnish a line in the *K*-spectrum. Now it may happen that the electron which rushes to take the vacant place comes from the ring next to the *K*-ring, or from the

ring next but one, or from the ring next but two, and so on. It is not at all likely to come from a very far-off ring, so we may say that it will come from the *L*-ring, or the *M*-ring, or the *N*-ring. But the farther off the ring from which it comes the greater is the energy liberated, and the higher the frequency of the resultant radiation or, what comes to the same thing, the greater the hardness of the resultant radiation. So that an electron which falls from the *N*-ring to the *K*-ring will give a harder radiation, *i. e.*, one of smaller wave-length, than an electron which falls from an *M*-ring to a *K*-ring, and harder still, of course, than an electron which falls from an *L*-ring to a *K*-ring. At the same time, it is more *likely* that the missing *K*-ring electron will be replaced from the ring next to it, the *L*-ring, than from the other more distant rings. And, as between the *M*- and the *N*-rings, an electron is more likely to come from the *M*-ring than from the *N*-ring. So that we should expect the least hard line in the *K*-spectrum, the one due to the passage of an electron from the *L*-ring to the *K*-ring, to be also the strongest line, since

the proportion of atoms where this particular change is occurring is the largest proportion. And, by the same reasoning, we should expect the hardest line, the one due to the passage of an electron from the *N*-ring to the *K*-ring, to be also the weakest line. The other line, the one due to the passage from the *M*-ring to the *K*-ring, would be intermediate, of course, both in strength and hardness. Thus our theory explains the observed fact that the hardest line is the weakest and that the softest line is the strongest, while the other line is, of course, intermediate in both respects.

A similar explanation holds good for the *L*- and *M*-groups of the *X*-ray spectrum. The bombardment will sometimes detach an electron from the *L*-ring. It is to be noticed that the energy necessary to do this is less than in the case of the *K*-ring, and that for two reasons. In the first place, the electrons in the *L*-ring are farther removed from the nucleus than the electrons in the *K*-ring, and in the second place they are subject to a certain repulsive effect from the electrons of the *K*-ring. All electrons repel one another. An electron

belonging to any ring is repelled by the other members of that ring, as well as by the members of other rings. As we get farther away from the nucleus this effect becomes more marked, and it acts, to a first approximation, as if the charge on the nucleus had been reduced, and therefore exerted a less firm binding effect on the electron. It requires less energy, therefore, in the case of any given element, to detach an electron from the *L*-ring than from the *K*-ring. The electron having been detached the vacant place may be occupied by an electron from any of the farther outlying rings. And, here again, an electron is more likely to come from the next farther ring than from a more distant ring. At the same time, the passage of the electron from the nearer ring will radiate less energy than the passage from a more distant ring. So that in this case also the weaker line should be the harder. This agrees with the experimental results.

The same general remarks apply to the detachment and replacement of an electron from the *M*-ring, with the difference that the detachment is still easier than in the case of the

L-ring. The *M*-ring is farther from the nucleus and also the repulsive effect of the inner electrons is more noticeable.

§ 4. *Doublets*

The simplicity of the *K*-spectrum is due to the fact that we are here concerned only with the innermost electrons of the atom and, in this region, the charge on the nucleus exerts a very firm control. The stability of the electrons close to the nucleus is very considerable. As we get farther away from the nucleus, however, the conditions become more complicated and the resulting spectra, indicating what changes are going on, also become more complicated. When we reach the outer electrons, those concerned in producing the visible spectrum, the changes going on are of the greatest complexity. This growth in complexity is apparent directly we pass from the *K*-spectrum to the *L*-spectrum. The *L*-spectrum contains more lines than the *K*-spectrum, and their explanation is less simple. An interesting feature of the *L*-spectrum is the large number

of doublets it contains. It is found that close pairs of lines may be distinguished in the *L*-spectrum and that the distance between these pairs is constant. It is this fact, that the doublets are of the same size, as it were, that calls for explanation. The explanation offered by the theory is that the *L*-ring is not really a single ring, but consists of two or more rings, each ring corresponding to a slightly different energy level. Let us suppose that the *L*-ring really consists of two rings. Then an electron from the *M*-ring may fall on to one or the other of these two rings. We shall denote these two *L*-rings by L_1 and L_2.

If an electron falls from the *M*-ring on to the L_1-ring, it will radiate an amount of energy slightly different from that radiated by an electron falling from the *M*-ring on to the L_2-ring. The wave-lengths corresponding to these radiations will therefore be slightly different and the corresponding lines in the spectrum, indicating these wave-lengths, will therefore consist of a pair of lines close together—a doublet. Now let us consider what happens when the electrons fall from the *N*-ring. The

electron which falls from the N-ring, whether it falls on the L_1- or the L_2-ring, will radiate more energy than the electron from the M-ring. But the *difference* in the energy radiated, depending on whether it falls on to the L_1- or the L_2-ring, is obviously the same as the corresponding difference in the case of an electron falling from the M-ring. It is the difference in the two paths which is concerned, and this difference is simply the distance between the L_1- and the L_2-rings. In the case of electrons falling from the N-ring, therefore, although the actual amounts of energy radiated are greater, and therefore the corresponding wave-lengths are shorter, yet the resulting pair of lines are at the same distance apart as in the case of the M-ring. Similar reasoning applies to any pair of electrons which start from the same outer ring and fall, one on the L_1-ring, and the other on the L_2-ring. In each case, a doublet is produced, and all these doublets have their component lines separated by the same interval.

This theory gives a satisfactory explanation of the observed equality of the L-doublets, but

we can go on to deduce a result from it which can be used as a test. We have seen that the *K*α-line in the *K*-spectrum is produced by the passage of an electron from the *L*-ring to the *K*-ring. But there are two *L*-rings. The passage of an electron from each of these to the *K*-ring should produce a line in the *K*-spectrum. These two lines should be very close together; they should form a doublet. Now we have seen that the *K*α-line actually is a doublet. But we can go further. The *difference* in path, according to whether the electron falls on the *K*-ring from the L_1- or the L_2-ring, is the same as the difference in the paths of two electrons, coming from the same outer ring, but falling one on the L_1-ring and the other on the L_2-ring. So that the interval between the components of the *K*-doublet should be the same as the interval between the components of the *L*-doublets. This result is confirmed by actual measurement. The "interval" or "distance" between the components of a doublet is really a difference, of course, in the hardness of the corresponding waves.

We have said sufficient to make the main

lines of the theory clear. We need only add that the further explanation of the *L*-spectrum and also of the *M*-spectrum requires us to assume that the *M*-ring also is not a single ring, but consists of two or more.

INDEX

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